Automation & Characterization of US Air Force Bench Top Wind Tunnels

Summary Report

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ABSTRACT

The United States Air Force Precision Measurement Equipment Laboratories (PMEL) calibrate over 1,000 anemometer probes per year. To facilitate a more efficient calibration process for probe-style anemometers, the Air Force Metrology and Calibration Program underwent an effort to modernize the existing PMEL bench top wind tunnels. Through a joint effort with the Department of Energy's Oak Ridge National Laboratory, the performance of PMEL wind tunnels was improved. The improvement consisted of new high accuracy sensors, automatic data acquisition, and a software-driven calibration process. As part of the wind tunnel upgrades, an uncertainty analysis was completed, laser Doppler velocimeter profiling was conducted to characterize the velocities at probe locations in the wind tunnel, and pitot tube calibrations of the wind tunnel were verified. The bench top wind tunnel accuracy and repeatability has been measured for nine prototype wind tunnel systems and valuable field experience has been gained with these wind tunnels at the PMELs. This report describes the requirements for the wind tunnel improvements along with actual implementation strategies and details. Lessons-learned from the automation, the velocity profiling, and the software-driven calibration process will also be discussed.

1. Introduction

The United States Air Force Metrology and Calibration (AFMETCAL) Program, headquartered in Heath OH, manages a network of over 80 individual Precision Measurement Equipment Laboratories (PMEL). The purpose of a PMEL is to calibrate test, measurement, and diagnostic equipment (TMDE). Regional PMELs calibrate over 1,000 anemometer probes every year for United States Air Force (USAF) customers. Precise air velocity measurement is required to support a variety of workplace environmental systems and weapon maintenance systems. The regional PMEL's utilize bench-top wind tunnels as standards to perform requisite calibrations. These standards recently underwent an improvement in sensor technology and automation techniques to allow PMELs to capitalize on modern data acquisition and computation methodologies. The project was initiated with Oak Ridge National Laboratory (ORNL) by the AFMETCAL Detachment 1, Heath OH and funded by the Department of Defense Joint Service Metrology Research and Development Program Calibration Coordination Group (CCG)[1].

The need for these improvements is driven by the fact that manufacturers continue to tighten the uncertainty specifications in anemometer products. It is essential for United States Air Force (USAF) to maintain standards that have an appropriate Test Uncertainty Ratio (TUR) with the improved TMDE. Since some TURs were approaching 1:1, a requirement existed to upgrade the existing bench-top wind tunnels. ORNL was tasked to upgrade the wind tunnel sensors and to individually calibrate each regional PMEL wind tunnel with a Laser Doppler Velocimeter (LDV) system and NIST-traceable Pitot tube. With improved sensors and specific LDV and Pitot tube calibrations, the automated wind tunnels now have a better uncertainty especially in the low flow regime of velocities less than 3 m/s.

The location of the nine PMELs were the AFMETCAL site in Heath Ohio, Robins Air Force Base (AFB), Tinker AFB, Hill AFB, Kadena AB, Feltwell AB, Elmendorf AFB, Vandenberg AFB, and Cape Canaverel AFS.

2. Bench-Top Wind Tunnel Requirements

The bench-top wind tunnels (BTWT) are work horses for the PMELs in calibrating anemometers. The anemometer's performance has steadily improved and the time and effort to calibrate the anemometers needs to be reduced. These changes have led to the need to address the workload, measurement uncertainty, and the calibration process efficiency.

2.1. BTWT Workload

The USAF utilizes anemometers for various applications. Requirements exist to measure air velocity in support of workplace environmental monitoring, weather conditions analysis, and to gather wind speed data. USAF industrial hygienists use air velocity TMDE to ensure workplace compliance with USAF Occupational, Safety, and Health regulatory standards. For example, the air velocity in room ventilation systems requires monitoring to ensure that specific air exchange rates are maintained. Other areas with such stringent requirements include paint spray booths, fume hood areas, and hospital operating rooms. Other USAF air velocity TMDE applications include the monitoring of weather conditions at remote landing strips and the measurement of wind speed during ordnance loading procedures. It is critical for anemometers to be properly calibrated to support these vital processes.

2.2. Uncertainty

Manufacturers continue to tighten the uncertainty specifications in anemometer products. It is essential for USAF to maintain standards that have an appropriate Test Uncertainty Ratio (TUR) with the improved TMDE. Since some TUR’s were approaching 1:1, it became necessary to upgrade the existing bench-top wind tunnels. ORNL was tasked to upgrade the wind tunnel sensors and to individually calibrate each regional PMEL wind tunnel with a Laser Doppler Velocimetry (LDV) system. With improved sensors and specific LDV calibrations, the automated wind tunnels now have improved uncertainty limits.

2.3. Wind Tunnel Efficiency

The current process of performing anemometer calibrations consists of setting up the Test Item (TI) and manually adjusting a variable potentiometer to set individual air velocity rates. The calibration technician then manually records differential pressure, temperature, relative humidity, and barometric pressure readings. An algorithm is then used to compute standard air velocity rates from the individual parametric data for comparison with the TI. The process of manually recording data and computing air velocities is cumbersome, time consuming, and has the potential for human error. Due to the volume of anemometer workload, a more efficient wind tunnel system was required. With the Wind Tunnel Automation Package, the entire process of setting air velocity rates, acquiring raw data, and computing standard air velocity values has been automated with improved performance (less time and less human errors).

3. Technical Approach

A typical bench top wind tunnel, which incorporates a conventional wind tunnel design, is shown in Figure 1. The instrumentation package and computerized data acquisition and control (DAC) system are also shown in the figure. The bench top wind tunnel is essentially a venturi with a 10cm x 10cm throat area (Figure 2). The geometry and upstream honeycomb flow straighteners produce laminar flow with very little turbulent intensity (<1%) in the test section. The velocity in the throat area is correlated against the pressure drop from the inlet to the throat. Pressure, temperature, and humidity are also measured to convert the velocity measurement to standard velocity units. The BTWT manufacturer has defined a specific location in the wind tunnel test section to locate devices to be calibrated. TMDE velocity probes are then placed at this location to perform a NIST-traceable calibration. The range of velocities covered by the BTWT is 0.15 meters/second (m/s) to 45 m/s. To achieve the full spectrum of velocities, it is necessary to use two nozzle plates. A nozzle plate is shown in Figure 3. These plates will choke (or reduce) the flow moving through the wind tunnel test section to allow generation of slower air velocities. The wind tunnel delivers velocities in three ranges. With no nozzle plate the wind tunnel covers the range of 7.5 m/s to 45 m/s. With the larger holed nozzle plate, the range is 1.25 m/s to 7.5 m/s, and the smaller holed plate goes from 0.15 m/s to 1.25 m/s. These ranges are often referred to as high, mid, and low.

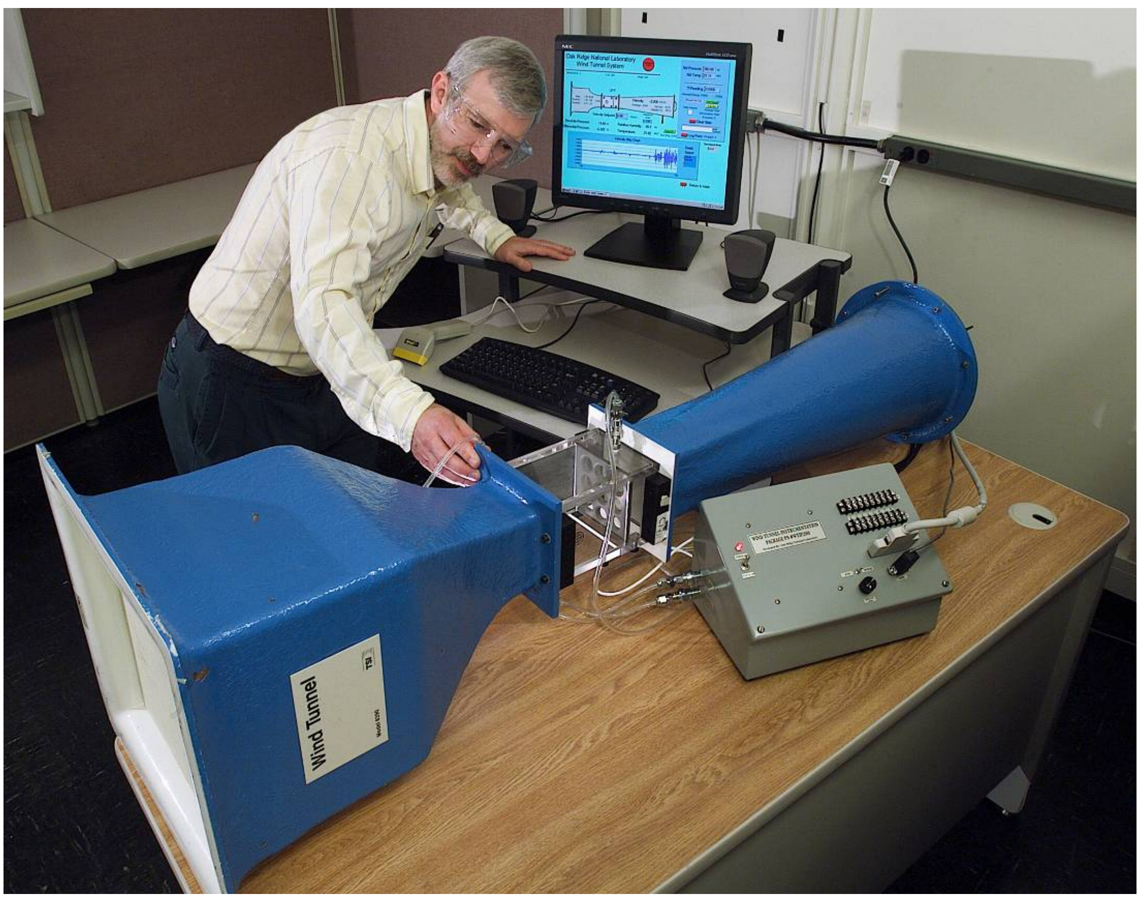

Figure 1. BTWT with Instrumentation Package and Data Acquisition and Control System

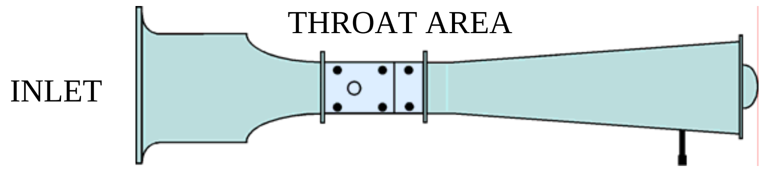

Figure 2. BTWT Schematic Diagram

Figure 3. Nozzle Plate for Creating Low Velocities

The typical calibration consisted of placing the device under test (DUT) in the wind tunnel, manually adjusting a control knob to set the flow rate, manually recording the pressure, temperature, humidity, and pressure drop at each set point, and then repeating this process for the rest of the calibration points. Once the calibration testing was complete the data was typed into a spreadsheet and algorithms were run to convert the data into standard flow velocity units and a calibration report. This process was time consuming and had a significant potential for transcription errors.

The entire calibration process was reviewed by Air Force and ORNL personnel with the goals of reducing the uncertainty in the velocity measurement, reducing the time to complete a calibration, and increasing the overall throughput of the calibration process. From this review, two approaches were adopted to meet the goals. The first approach was to complete a thorough uncertainty analysis and the second approach was to automate a significant portion of the calibration process and the data archival/retrieval methods.

A study was also undertaken to review calibration methods for the BTWT. After investigating various options, a Pitot tube and a LDV were chosen for calibrating the BTWT. A NIST-calibrated Pitot tube was used for flow velocities of 8 m/s and higher. A LDV was used for flow rates from 0.15 m/s to 8 m/s. Below 8 m/s the Pitot tube measurement uncertainty increased significantly and recently NIST has selected LDV methodology for a standard for low gas flow.

3.1. Uncertainty Analysis - Initial

A generalized uncertainty analysis was used to determine the sensitivity of the various parameters that affect the wind tunnel performance. Discounting losses and assuming the density is constant over the limited pressure drop occurring within the system, Bernoulli's Equation for the wind tunnel may be written as:

$$\text{Bernoulli's Equation: } \frac{P_1 - P_2}{\rho} \approx \frac{1}{2}\left[V_2^2 - V_1^2\right]$$

Where P_1 and P_2 are the upstream and throat pressures, respectively, V_1 and V_2 are the upstream and throat velocities, respectively, and ρ is the fluid density.
The process measurement locations are shown in Figure 4.

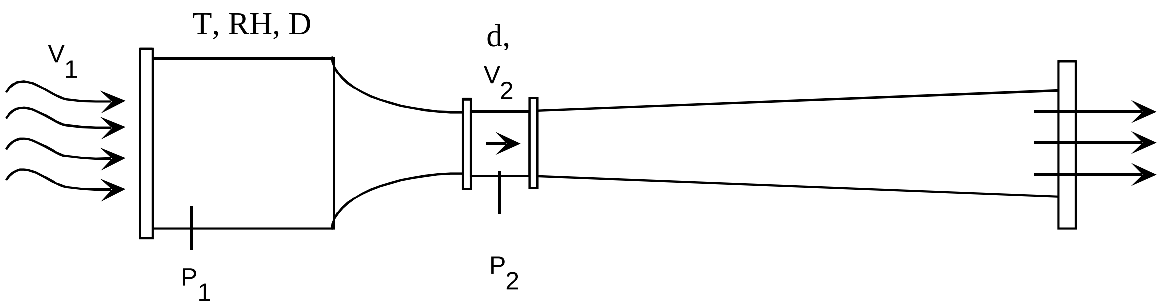

Figure 4. Flow and Measurement Diagram of BTWT

Using continuity and substituting β = (throat diam, d)/(inlet diam, D), yields

$$V_2 = \frac{\sqrt{2}}{\sqrt{1-\beta^4}} \frac{1}{\sqrt{\rho}} \sqrt{\Delta P}$$

where ρ is a function of pressure, temperature (T), and relative humidity (RH) and ΔP is the differential pressure (the difference between P_1 and P_2). This expression may be evaluated using the standard expression for measurement uncertainty to produce the sensitivity coefficients for the input quantities P, ΔP, T, and RH[2].

$$u_c^2(v) = \left[\frac{\partial V}{\partial P}\right]^2 u_P^2 + \left[\frac{\partial V}{\partial \Delta P}\right]^2 u_{\Delta P}^2 + \left[\frac{\partial V}{\partial T}\right]^2 u_T^2 + \left[\frac{\partial V}{\partial RH}\right]^2 u_{RH}^2$$

Evaluation of these terms for the BTWT system showed that the differential pressure (ΔP) measurement is the most significant contributor to the uncertainty, followed by the pressure measurement. The T and RH measurements had only slight contributions to the uncertainty; however, all parameters were included in the analysis. As would be expected, the maximum static uncertainty of the wind tunnel system will occur at the low end of each airspeed range, where the uncertainty component of the differential pressure cell generates a significant component of the overall uncertainty. The overall uncertainty analysis is described in detail in the Appendix A.

3.2. Wind Tunnel Instrumentation

With the initial results from the uncertainty analysis, upgrading of the wind tunnel process instrumentation was needed to reduce the measurement uncertainty of the wind tunnel velocities. The upgrade included the absolute pressure transducer, the differential pressure sensor, and the temperature/relative humidity sensor. The original values and the corresponding improved uncertainties are listed in Table 1.

Table 1 Uncertainties of the BTWT Instrumentation

PARAMETER	ORIGINAL UNCERTAINTIES	UPGRADED UNCERTAINTIES
Absolute Pressure	**±0.04% FS**	**±0.15% Reading**
Differential Pressure	**±0.5% FS**	**±0.014% FS**
Temperature	**±0.2 K**	**±0.1 K**
Humidity	**Not specified**	**±2.0% RH (0-90% RH)**

The most significant improvement was made in the differential pressure transducer; going from 0.5% of full scale to 0.014% of full scale. At the low end of a velocity range, where the uncertainty is the highest, the ΔP measurement's uncertainty is reduced by more that an order of magnitude. The other three process instruments uncertainties were also reduced some but their effect on the overall measurement were not near as significant as the ΔP measurement. The upgraded absolute pressure transducer was calibrated over a narrow range of expected operational values. In doing this, the ±0.15% of reading device had less uncertainty than the original pressure transducer at ±0.04% of full scale. In addition, the upgraded instrumentation is connected into a data acquisition board in a personal computer that allows the data to be archived, displayed, and manipulated. The uncertainty of the analog input board is ±0.01% of reading (original system readout device was ±0.25% of reading).

The NIST-calibrated Pitot tube expanded uncertainty (with a coverage factor of 2) was determined to be ±0.36 % at 7.55 m/s, ±0.32% at 10 m/s, and ±0.29% for velocities at or above 15 m/s. This data is from the NIST calibration performed during September 9-12, 2000. The LDV system was calibrated at ORNL and found to have an uncertainty of ±0.20% over it entire range of 0.15 to 45 m/s.

3.3. Uncertainty Analysis - Finalized

Overall uncertainty of the upgraded wind tunnel automation package (WTAP) is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. In practice, however, the upgraded ΔP transducer calibrated much better than manufacturer's specification at the low end, i.e. to within 0.04% of reading as opposed to .014% of full scale. This calibration was accomplished using a cross-floated dead weight testing scheme to provide accurate standard differential pressures from 0 to 5 torr ±0.00186 torr. Currently, however, Air Force field standards for differential pressure (i.e. Hooke Gages) do not provide for calibration to this level of uncertainty. Calibration with these field standards provides a 0.005 torr uncertainty in the differential pressure measurement, which is an uncertainty greater than the manufacturer's specification for the differential pressure unit. Using this higher uncertainty value for the differential pressure measurement results in an increase in static uncertainty throughout the wind tunnel's range of use. Over the full range of use of the wind tunnel, the overall WTAP uncertainty was calculated with a coverage factor of one and is shown in Table 2 and in Figure 5. An average uncertainty value was used in Figure 5 for the original WT over each range; e.g. 6.95% for the 0.15 to 0.3 m/s range.

Table 2 Overall Uncertainty of BTWT

Calibrated Range	WTAP Uncertainty	Original WT Uncertainty	Nozzle Plate
0.15 to 0.3 m/s (30-60 fpm)	2.5% of reading	8.6 to 5.3% of reading	#2
0.3 to 1.25 m/s (60-250 fpm)	1.5% of reading	5.3 to 2.8% of reading	#2
1.25 to 3 m/s (250-600 fpm)	1.75% of reading	4 to 2.8% of reading	#1
3 to 7.5 m/s (600-1500 fpm)	1.5% of reading	2.8 to 2.3% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	2.0 to 1.75% of reading	Open
10 to 45 m/s (2000-9000 fpm)	1.0% of reading	1.75 to 1.15% of reading	Open

The range of uncertainty values for the original WT comes from the manufacturer's values that contain a fixed uncertain as a percent of reading plus a constant. For flow from 0.15 to 1.25 m/s the uncertainty is listed as 2% of reading plus 0.01 m/s, for the 1.25 to 7.5 m/s range the uncertainty is 2% of reading plus 0.025 m/s, and for the 7.5 to 45 m/s range the uncertanty is 1% of reading plus 0.075 m/s.

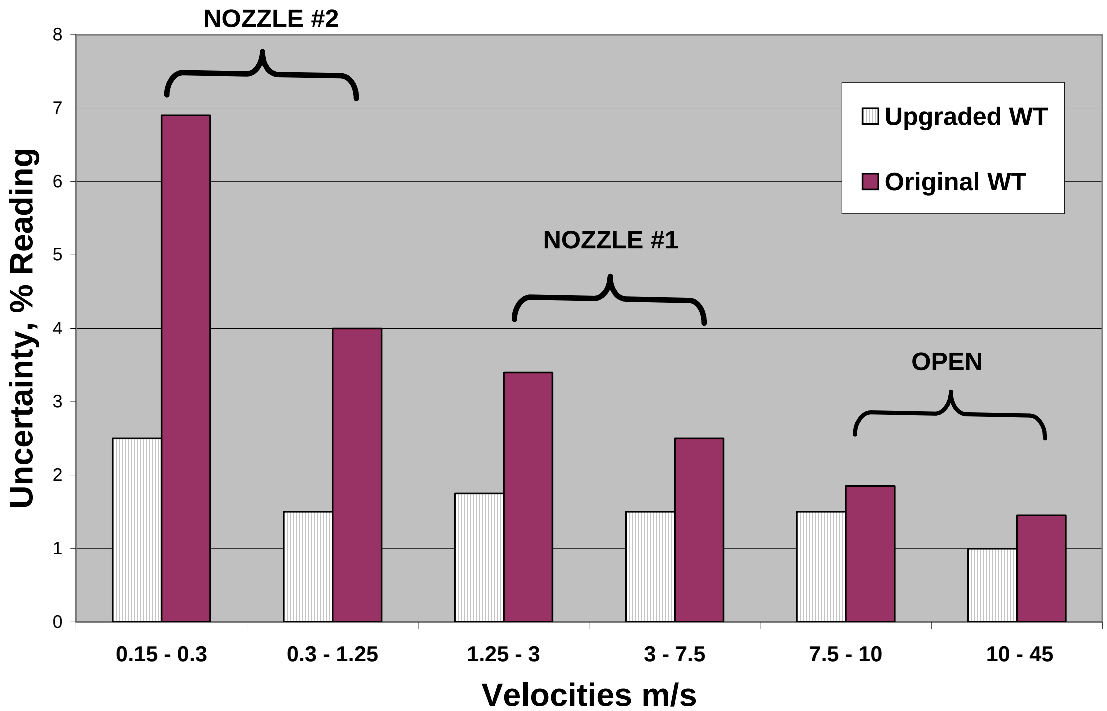

Figure 5. BTWT Uncertainty Values

The WTAP has significantly lower uncertainty in all velocity ranges but especially in the low flow regime of 0.15 m/s to 3.0 m/s where it is approximately two to three times lower than the original wind tunnel value.

3.4. Automation

To increase the efficiency and accuracy of the calibration process, the measurement process was automated via a personal computer, remote blower control, and software-driven calibration. This includes automatically acquiring data from the wind tunnel instrumentation (absolute pressure (P), differential pressure (ΔP), air temperature (T), and relative humidity (RH)), converting this data to an air velocity, displaying the information, and archiving the calibration data. The only portion of the process that was not automated is the data acquisition from the device under test. This data is manually entered into the automation software and then is stored for comparisons, archiving, plotting, etc. This automation step was not completed because of the variety of output signal types and amount of effort required to develop interfaces for each of them.

A software program was written in Labview to automate the various functions. The Air Velocity Generation/Calibration screen (Figure 6) is the main workhorse of this program.

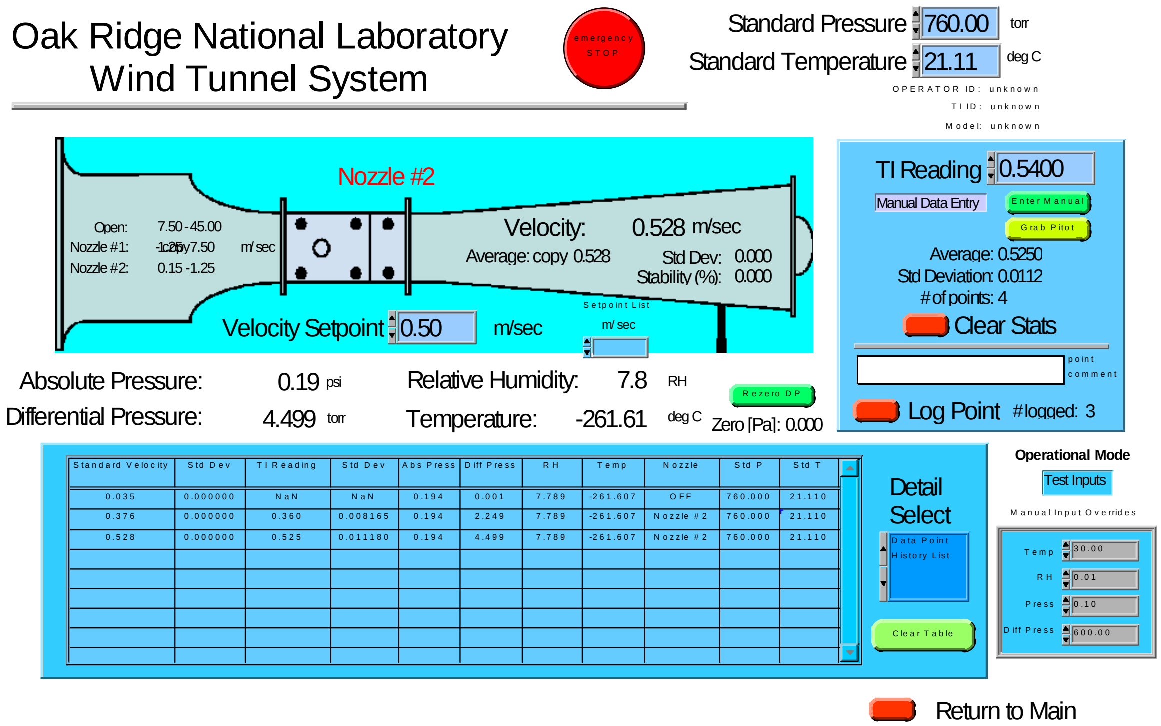

Figure 6. Wind Tunnel Velocity Generation/Calibration Automation Display

It is through using this screen that all test instruments are calibrated. The screen is comprised of several different block areas; on the upper left hand of the screen is a diagram of the wind tunnel. Superimposed over the diagram are indicators providing the current wind tunnel configuration range (open tunnel, nozzle #1, or nozzle #2), the current airspeed (in a variety of units), the current average airspeed, and the standard deviation of data points used for averaging purposes. A data entry box is also provided which enables the entry of the desired velocity setpoint. If the system is in automatic control, this entry box controls the setpoint for the automatic control system. In both manual and automatic mode, entry of the desired manual setpoint will provide prompting information such that the appropriate nozzle is installed for the target airspeed range.

Below the wind tunnel diagram are indicators for the current absolute pressure, differential pressure, relative humidity, and temperature. These display fields are updated continuously. Following each numerical indication (including the airspeed of the wind tunnel diagram) there is a pull down selector that enables the operator to select the engineering units for each instrument. Selecting an engineering unit will result in all subsequent displays for that variable to be scaled to the specified engineering unit. Data logging and archival will also be performed using the selected unit system.

Adjacent to the pressure/temperature/relative humidity display area is a green button labeled “REZERO DP”. As all differential pressure cells will experience some bias drifting, this button provides the ability to zero the differential pressure cell. All subsequent operations within this panel will then be conducted using the newly provided zero-value of the differential pressure cell.

In the upper right hand corner of the screen are data entry fields for Standard Pressure and Standard Temperature entry.

The operator may specify the standard conditions used by the test device, including the engineering units. These values will be used to correct all wind tunnel air velocity indications to these standard reference conditions.

Below the Standard Conditions entry area is a text display that indicates the current operator identification number, and the current Test Instrument, as entered in the logon screen.

On the right hand side of the screen is a TEST INSTRUMENT (TI) data entry area. In this entry area, the user may manually enter the device indication of the Test Instrument, or (when applicable) may specify the system to obtain this information automatically as a voltage input on terminals 6, 7, or 8 of TERMINAL strips + and -. In the former case (manual entry) the user must press the green “ENTER MANUAL” button or the RETURN key each time they require a TEST INSTRUMENT reading to be entered. The system will accumulate data points and performs statistical analysis on the data (average, and standard deviation). Thus, for each airspeed setting, the user may enter Test Instrument readings, until the statistics are acceptable. The data point may then be logged to an archive file by pressing the LOG POINT button, for later data analysis and reporting purposes. A comment may be entered for each log point to help in later data analysis.

Also in this data entry area is the CLEAR STATS button. This button provides the ability to clear all statistics to start with a fresh dataset. This button can be pressed whenever statistics need resetting, i.e. after stabilizing at a new velocity setpoint, after logging a set of data, etc.

On the bottom of the air velocity generation panel is a user selectable graphical interface. Based on the operator’s selection (at the right of this area), this graphical display can be used to display a strip chart indicator of the airspeed, the differential pressure, the absolute pressure, the relative humidity, and the temperature. Additionally, a table may be selected that provides a log of all the data points logged to an archive file.

On the lower right hand of the panel is another user entry area that allows the operator to select the operation mode of the system; normal, test, and tuning. In normal mode, all instrumentation signals are acquired automatically be the computer operating system and are converted to engineering units based on calibration data entered in other areas of the software. In test mode, the operator may override automatic data entry with user specified input voltages for each channel (P, ΔP, T, RH). This is convenient for debugging purposes, or to diagnose abnormal operations of the system. The tuning mode allows the operator to fine tune the automatic control logic for the closed loop control of the blower motor. Upon entering the TUNING mode, three parameters will be displayed which correspond to the proportional, integral, and derivative gains of the blower PID control system. These parameters should be adjusted properly from initial fabrication of the wind tunnel system; however, they can be adjusted to fine tune the PID automatic control logic for changes in blower operation over time.

On the top of the screen is an EMERGENCY STOP button. This button may be pressed at any time to stop the blower. Upon doing so, the velocity setpoint will also be automatically reset to 0.

Airspeeds may be generated either manually, by adjustment of a manual control knob on the instrumentation console, or automatically, by specification of an airspeed control setpoint, as described earlier. In either automatic or manual mode, it is advised that the operator input the desired airspeed setpoint in the entry box provided for this purpose. Upon doing so, the system will check if the appropriate nozzle is installed (dependent upon the target setpoint being within fixed airspeed ranges). If the appropriate nozzle is not installed, the user will be prompted to do so and will be requested to read in the nozzle to be installed with the barcode scanner (Figure 7).

In addition to automatically recording, displaying, and archiving the calibration data, the system has the capability to check for up-to-date instrumentation calibration, converts the data to selected engineering units, and stores pertinent calibration information such as serial numbers, operator, time and date, as well as any operator comments.

As part of archiving, a database package was created. The database operations screen allows the operator to retrieve archived calibration information about the Test Instrument and perform a variety of graphical analyses to evaluate that device.

The database operations screen (Figure 8) is comprised of several information boxes. On the upper left-hand of the screen, the identification number of the Test Instrument is displayed. Adjacent to this, specific device information is displayed including ID, manufacturer, model, serial number, owner, and last calibration date. This data corresponds to the data entered in the device logon screen.

Figure 7. Barcode scanner entry for a nozzle plate

Below this area, two selection tables are provided that show the date of all subsequent calibrations of that device (performed on the wind tunnel system). The user may select any one of these calibration dates in each box and display information on the device for that calibration, including the raw calibration data that was logged during the calibration, and several graphical displays including the TEST INSTRUMENT indication vs. the standard airspeed, the % rdg error vs. the standard airspeed, and the standard and device standard deviations vs. standard airspeed (for an idea of stability of systems during calibration). The ability to select from two boxes enables comparison of separate calibration runs against one another. A calibration report may be generated for the calibration data selected in the top selection box by pressing the GENERATE REPORT button.

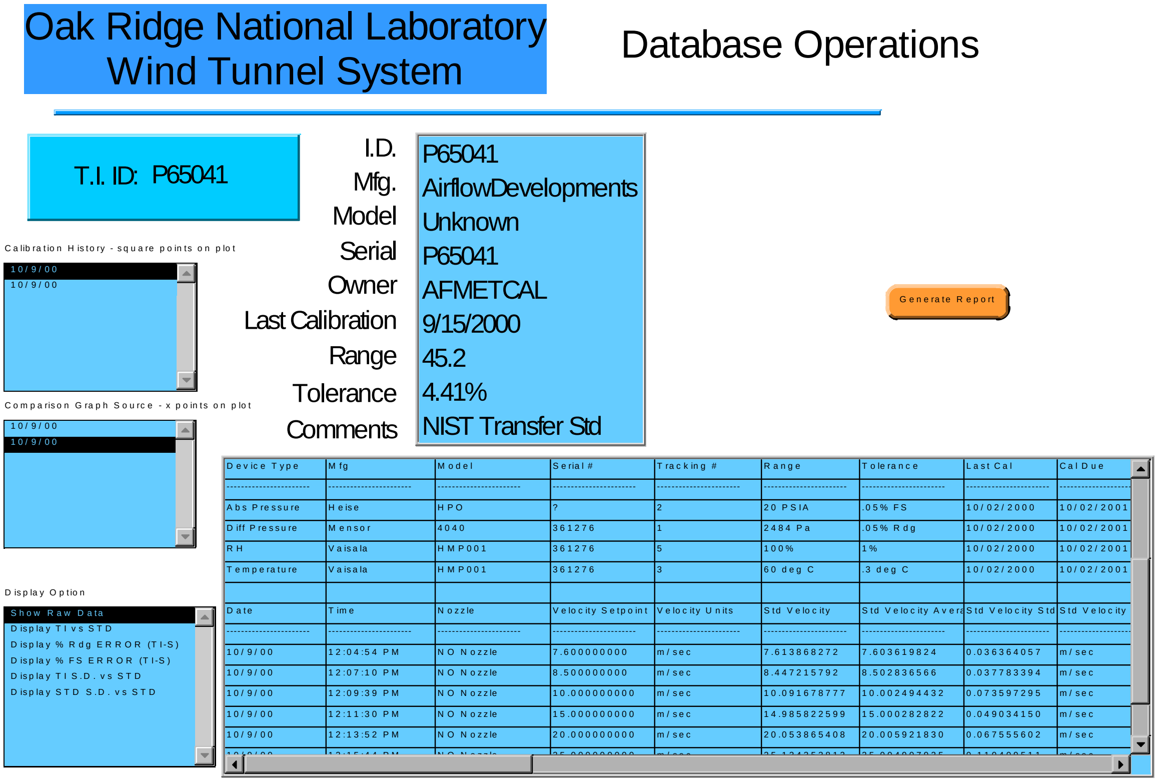

Figure 8. Database Operations Screen

4. Wind Tunnel Characterization

There are several aspects of the wind tunnel that were characterized as part of this effort. The placement or location of the device under test (the instrument to be calibrated) in the wind tunnel can affect the calibration results; thus, the best location was determined. The effect of the nozzle plates being installed incorrectly was investigated. The calibration of the wind tunnel standards was completed for the Pitot tube and the LDV.

4.1. Device Under Test Location

Proper test instrument placement is an important aspect of wind tunnel use. While the shape of the wind tunnel has been designed to provide a 10cm x 10cm x 10cm (4” x 4” x 4”) test area, flow development profiles require that only certain subregions of this measurement volume be used for calibration of test instruments.

The wind tunnel draws in relatively stagnant, ambient room air into the laminarizing intake honeycomb element. The air travels through a reducing section, where its velocity increases as its pressure decreases, per the Bernoulli theorem. When the air enters the Plexiglas measurement volume, which is comprised of a constant cross sectional geometry, it continues to accelerate for several centimeters past the start of the uniform cross sectional geometry region.

Using a laser Doppler velocimeter (LDV) the airflow velocity profiles have been characterized within the 10cm x 10cm x 10cm (4"x4"x4") measurement volume of the wind tunnel. The data presented in this section represents some of the more significant findings from several profiling sessions. Figures 9 and 10 are velocity profiles across the horizontal plane (normal to the axis of flow), at various upstream locations referenced to the nozzle plate. Each data point represents the average of 2000 points, obtained via LDV measurement of entrained moisture mist in the flow stream. LDV measurements are made by observing the frequency burst that results when entrained particles travel through an optical fringe pattern created by two intersecting laser beams. As the distance between optical fringes is dependent only upon the wavelength of laser light, and the intersection angle of two laser beams, the frequency burst gives a direct indication of particle velocity (i.e. distance traveled over a known time interval). Prior to running, the LDV system is aligned with the wind tunnel in all three axes by iteratively aligning intersecting/divergent beams with the chamber wall boundaries. The LDV may then be used to map out the velocity profiles within the tunnel, with positions referenced against an arbitrarily chosen location in the tunnel. For our tests, we referenced dimensional measurements from a point at the top, leftmost upstream edge of the nozzle plate insertion plane. For reference, the manufacturer labels and suggests using the wind tunnel at a location positioned in the midpoint of the chamber volume, at a location approximately 85 mm upstream of the nozzle plate insertion plane.

Using the LDV, velocities throughout the measurement volume were measured and velocity profiles characterized. The most striking finding was that there is significant flow development occurring with axial travel into the measurement volume. The velocity profile variation (change from a flat profile) increases as much as 1-2% per 10 millimeter (mm) of travel axially toward the nozzle plate location (Figs. 9 & 10). This finding indicates that profiles must be taken into account if the wind tunnels are going to be used at improved accuracy levels. The wind tunnel with Nozzle Plate #2 installed showed a much larger variation than with Nozzle Plate #1 installed. However, both plates created a flat velocity profile at 85 mm from the nozzle plate location. Additional data was taken and the same trends were measured.[3]

It is recommended that test instruments be positioned at a point 85-90 mm upstream of the nozzle plate insertion place, centered horizontally and vertically in the measurement volume. This is the same location as recommended by the wind tunnel manufacturer.

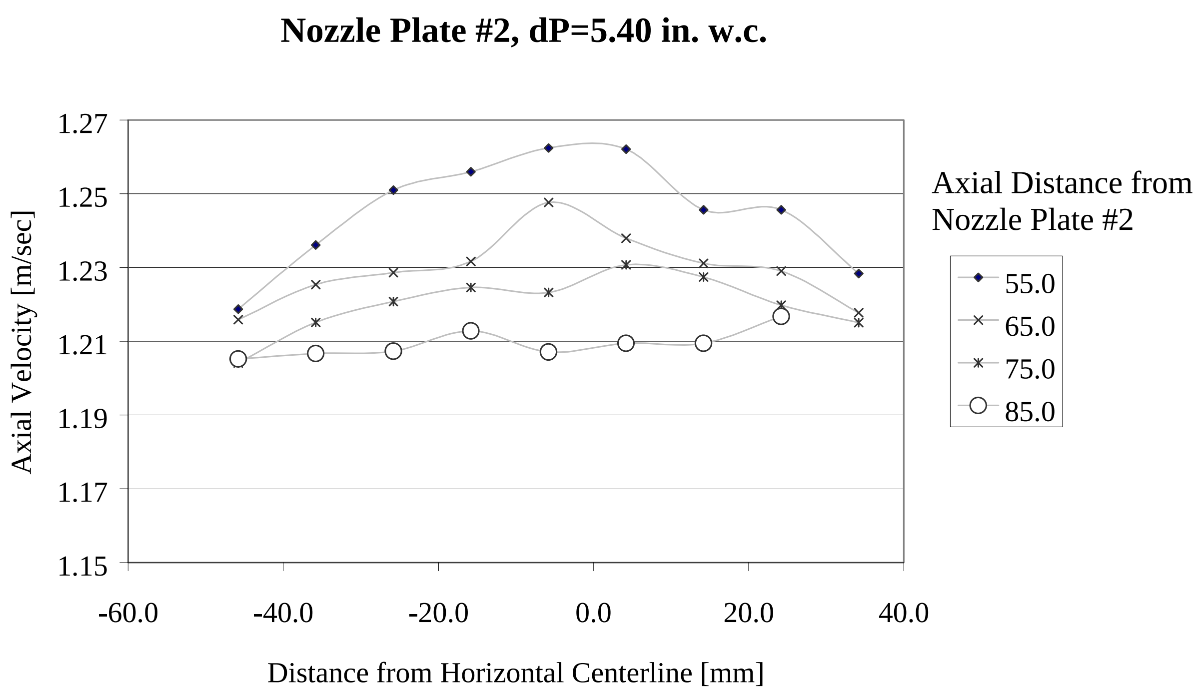

Figure 5. Horizontal Velocity Profile as a Function of Distance from the Nozzle Plate #2

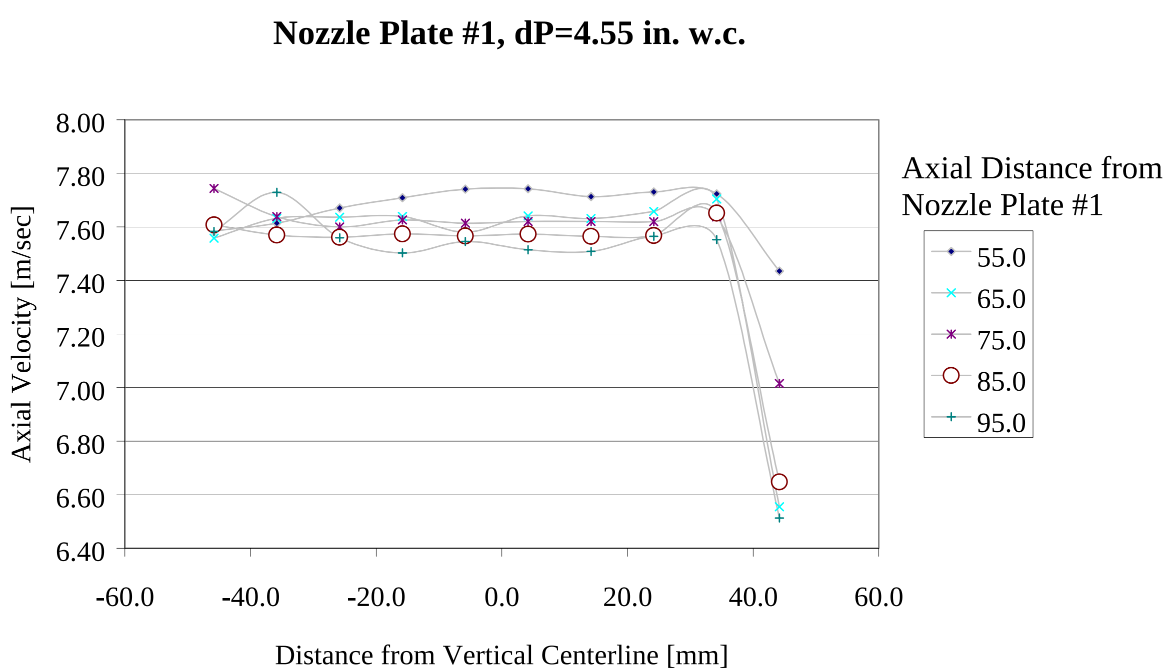

Figure 10. Horizontal Velocity Profile as a Function of Distance from Nozzle Plate #1

4.2. Nozzle Plate Installation Effects

The impact of improperly installing the restriction nozzle plates within the tunnel have been investigated by utilizing a very repeatable test instrument as a transfer standard and characterizing the wind tunnel with correct and backwards installment of the nozzle plates. The effect was evaluated throughout the lower and midrange of wind tunnel velocities (Nozzle #2 and Nozzle #1). This data is summarized in Figure 11. As indicated, improper installation results in gross error, reducing the wind tunnel velocity by 20-25% throughout the low and midrange of use.

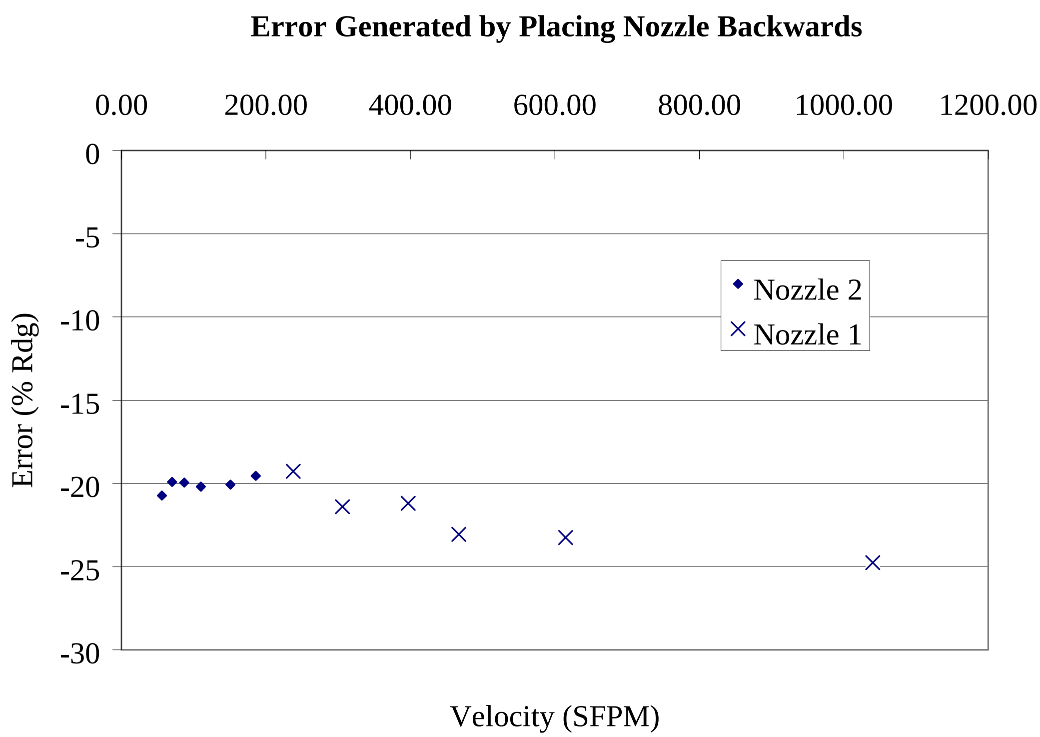

Figure 11. Effect of Nozzle Installation on Velocity Measurement

Nozzle plates should only be inserted with the rounded edge of the nozzles facing the upstream position, as indicated in Figure 12. Note that the nozzle plate label also faces the upstream position.

Figure 12. Correct Installation of a Nozzle Plate

4.3. Wind Tunnel Standards' Calibration Methodology

The wind tunnel design was originally calibrated by the manufacturer using an LDV system. This original calibration is used for all subsequent wind tunnels. The wind tunnel calibration coefficients are entered into the automation software via a calibration coefficient data table (Figure 13). The calibration data table provides for the entry of 3 sets of calibration coefficients, for the three different ranges of the wind tunnel (0.15 – 1.25 m/sec, 1.25 – 7.5 m/sec, and 7.5 – 45 m/sec). Three coefficients are entered for each range; a, b, and c for the standard equation:

$$V_s = a + b * \Delta Ps^c$$

where Vs is the velocity at standard conditions (70 deg F, 14.7 psia), and ΔPs is the 'standardized pressure drop' at these standard conditions.

To reduce the uncertainty for each wind tunnel, individual flow velocity calibrations were completed on each Air Force wind tunnel. For flow velocities at or above 8 m/s, the NIST-calibrated Pitot tube was used and for velocities below 8 m/s, the LDV system was used. The Pitot tube was calibrated in the NIST Dual Test Section Wind Tunnel[4] and a coverage factor of 2 was used for the data uncertainty. The measurement uncertainty ranged from 0.36% at 7.55 m/s to 0.29% at 45.2 m/s. However, the uncertainty at 5 m/s was 0.48% and was 4.4% at 1.76 m/s[5]. From this data, it was clear that a different instrument was needed for the low flow rates; thus the choice for the LDV. In practice, with the field process instrumentation (FlowCal 2000 Pitot Tube Calibrator), the uncertainty for the Pitot tube was set at $\pm$1%.

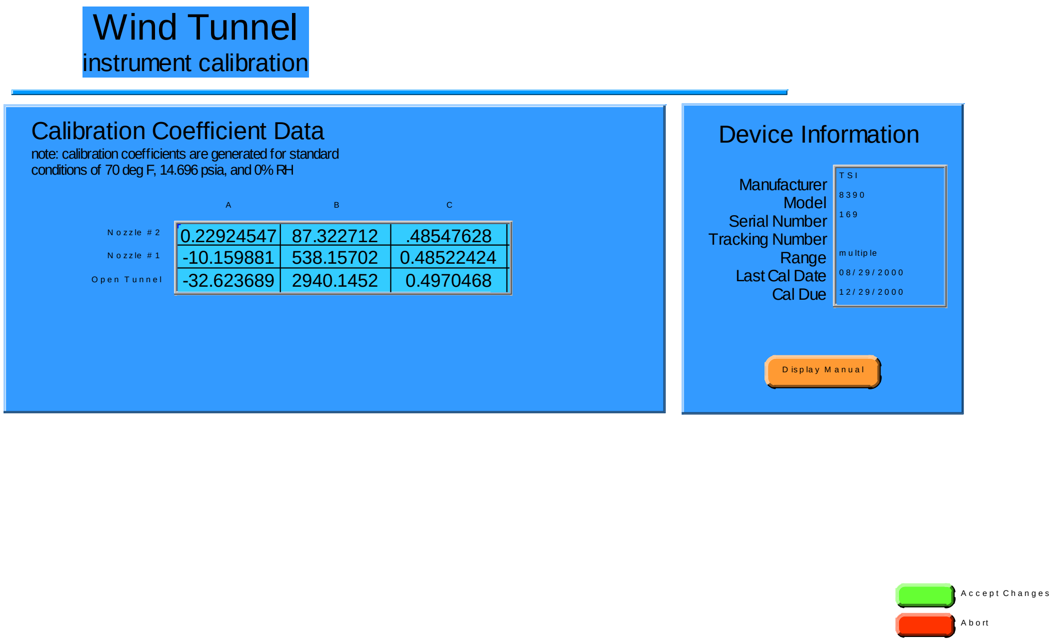

Figure 13. Wind Tunnel Original Calibration Coefficient Entry Screen

Calibration of the LDV was accomplished using two, independent methods based upon techniques developed at NIST[6]. These two methodologies are intended to provide independent methods for calibrating the velocity measurements of the LDV. The accuracy of the LDV is dependent upon knowing the angle of intersection of two laser beams, which cross to form a measurement region of interference fringes. When a particle travels through this fringe pattern of light and dark regions, a velocity dependent frequency is generated by the intermittent reflection of light off the particle. Knowledge of the wavelength of laser light used and the angle of the intersection of the beams provides the spatial characteristics of the interference pattern.

The first calibration method involves determining the angle of intersection of the laser beams by mapping similar triangles along the bisecting axis of laser intersection. Essentially, the distance between diverging or converging laser spots is determined at two points along the bisecting axis. Accurate determination of the distance between spots, and the distance along the bisecting axis provides measurement of the angle of the intersection of the beams. The LDV was attached to an X-Y-Z translation stage with 0.01 mm resolution and a calibrated accuracy of 0.05 mm.

The second methodology involves generation of a well-characterized particle motion through the intersecting beams of the LDV. An angular/linear velocity generator was constructed that comprised a machined aluminum disk which is driven by a motor. In the perimeter of the disk, a light trapping cavity was machined and a single thin wire is stretched across the gap, with the wire parallel to the axis of rotation of the disk. The thin wire was positioned to cross the interference fringe pattern of the LDV, thus acting as a particle of well-known velocity. The linear distance is known very accurately (center of rotation to the fine wire) and the angular velocity is measured by frequency monitoring of a chopped light during rotation.

The two calibration methodologies agreed very well with each other and had uncertainties of less than 0.2% for the velocity measurement and this uncertainty value is independent of the flow velocity for the range covered by these wind tunnels.

5. Results from Upgrading the BTWT

With the addition of the improved process instrumentation, the automation software, and calibration of the flow standards (LDV and Pitot tube), each of the nine BTWTs were calibrated over their entire flow range of 0.15 m/s to 45 m/s. The calibration for each individual wind tunnel is shown in Appendix B.

5.1. Pitot Tube Calibrations

The NIST-calibrated Pitot tube was used over the range of 8 m/s to 45 m/s for all nine wind tunnels. The calibration data is shown in Figure 14. The data is plotted as wind tunnel error (the difference between the Pitot tube and the wind tunnel reading) as a percent of reading versus the wind tunnel setpoint or velocity. The data are grouped fairly tightly with most of the wind tunnel data falling within $\pm$0.5% of the Pitot tube value. Below 10 m/s the uncertainty of the wind tunnel and the Pitot tube increases and this is borne out by the data in Figure 14 as well.

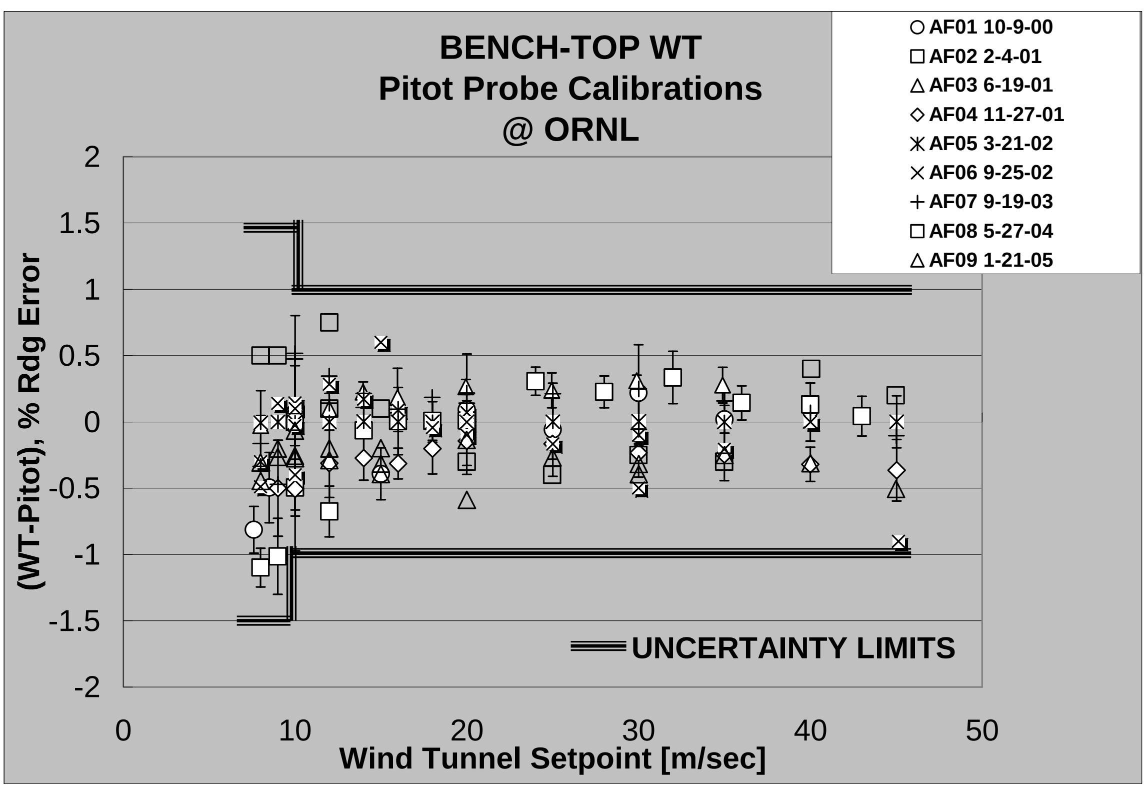

Figure 14. Pitot Tube Calibration of the BTWTs

5.2. LDV Calibrations

The LDV system was used over the range of 0.15 m/s to 8 m/s for all nine wind tunnels. The calibration data is shown in Figure 15. The data is plotted as wind tunnel error (the difference between the LDV and the wind tunnel reading) as a percent of reading versus the wind tunnel setpoint or velocity. Data were taken from 8 m/s to 35 m/s to compare with the Pitot tube values. These higher flow data seem to match the Pitot tube data in that most of the points fall within ±0.5% error range as did the Pitot tube data in Figure 15.

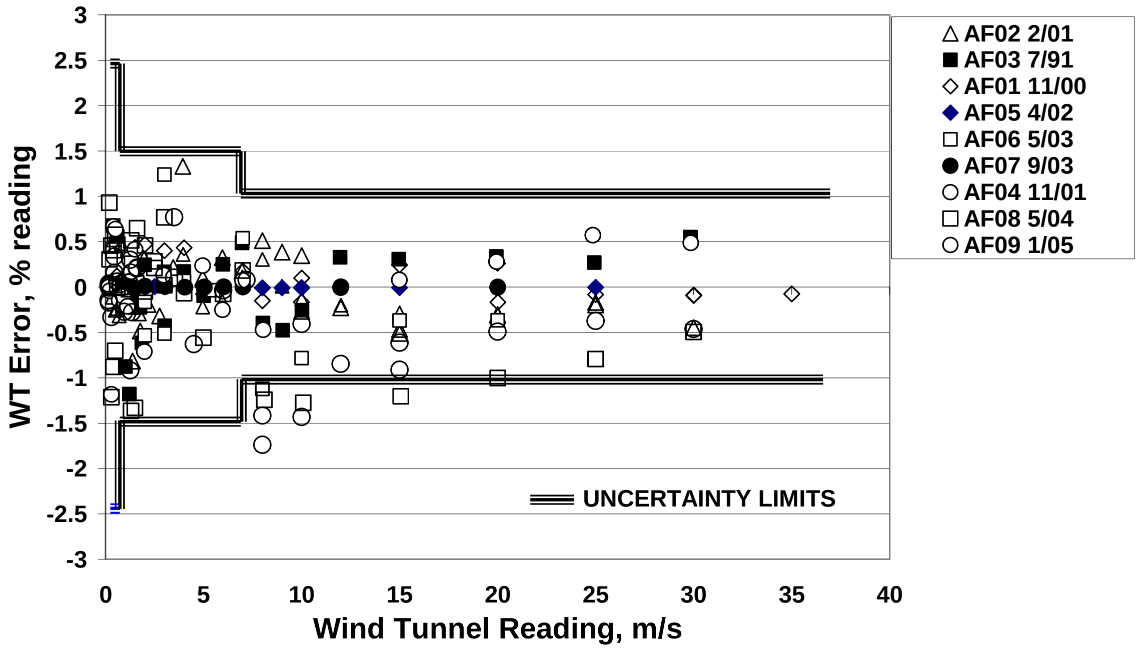

Figure 15. LDV Calibration of BTWTs

A comparison the LDV data with the Pitot tube data is shown in Figure 16. Very good agreement is shown between the two standards over the entire range of 8 m/s to 45 m/s.

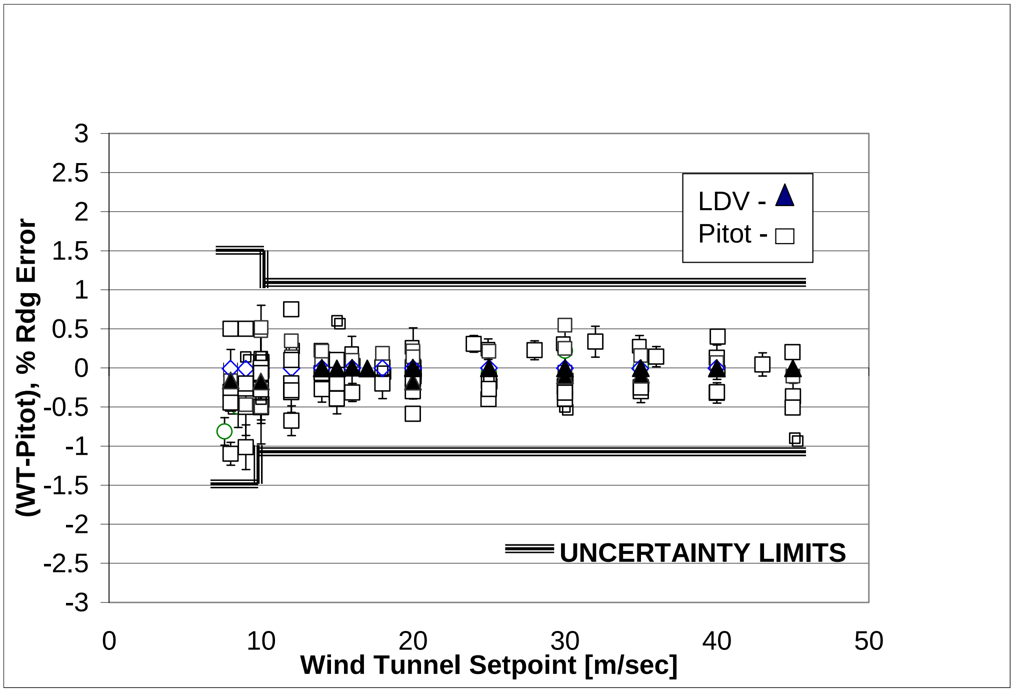

Figure 16. Comparison of LDV and Pitot Tube Data

An expanded view of the very low flow LDV data is shown in Figure 17. All the data are within the expected uncertainty limits. This data was collected over a three year period with nine different wind tunnels. This indicates that the calibration process is stable and repeatable for BTWTs and that all nine wind tunnels fall within the stated uncertainty limits.

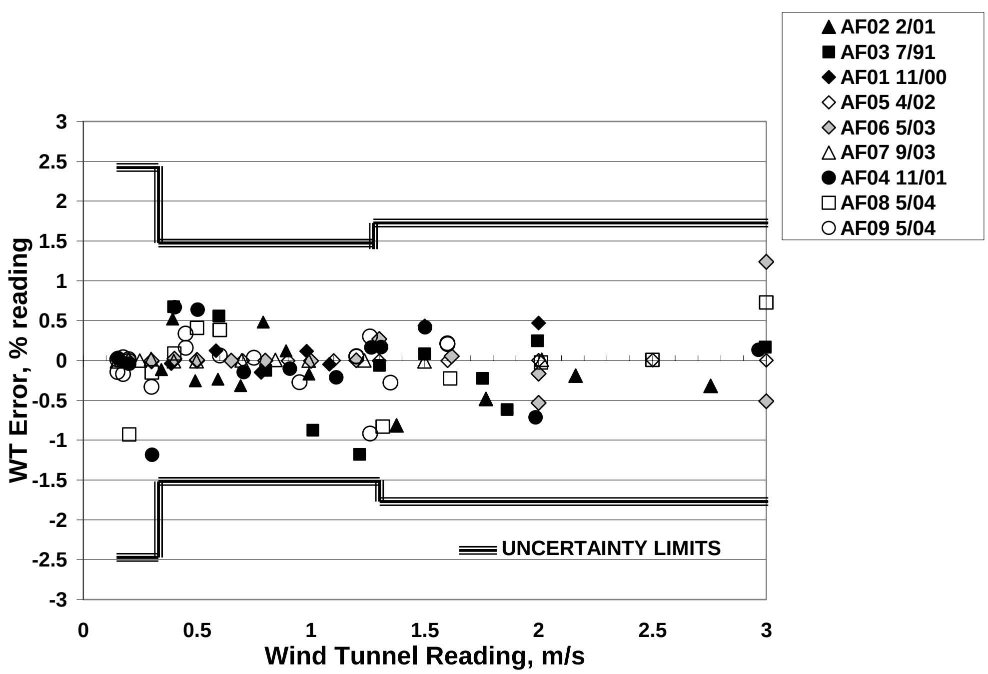

Figure 17. Low Flow LDV Calibrations of BTWTs

5.3 Field Experience with the BTWTs

A survey was sent to the nine PMELs that received the upgraded BTWT to obtain their experience with the system from initial start up to reliability to suggested improvements. A summary of the results (replies from six of the nine PMELs) is contained in this section.

The general consensus was that the system was very easy to initially set up. For the first installation, we accompanied the system and worked with the PMEL to set it up and conduct a test. From that experience and how well it went, we made the decision to develop a training document and a couple of one-page set up instructions. From the feedback we received as we shipped each system and this survey, the initial set up went very smoothly.

The consensus was that the system, after initial set up, is very user friendly and very few problems were encountered in conducting calibrations.

The automation portion of the software seems to save significant calibration time for the metrologists. The consistent estimate was that the time savings for the upgraded system was about 50% or calibrations were completed in half the time it took with the old system. Several reasons were stated around the time savings including that corrections to standard conditions are done automatically and that the averaging featuring was a help.

The system was perceived to be reliable with each system having one problem on average. The motor control board has failed on two systems and differential pressure sensor has shown some drift at one installation. No software problems have been noted as well as any computer hardware issues.

To the question about the most troublesome component or issue, several items were noted. The cable that connects from the wind tunnel instrumentation box to the computer does not attach securely and can come loose. Two PMELs noted that the calibration of the differential pressure sensor is time consuming and difficult (especially with the Hooke gage). There is an increased instability at low flow rates when nozzle plate #1 is installed. The standard deviation of the wind tunnel reading increases in the 300 to 500 feet per minute (FPM) range and causes difficulty in reading analog meters like the Kurz 443. Finally, a high altitudes, like at Hill AFB, the wind tunnel does not reach 8858 FPM and this is not addressed in the Technical Data Procedure.

The most useful feature of the system was the ability to archive and retrieve past calibration data on a particular test item. Also, the ability to automatically average the data and to have direct readings in engineering units were noted as very useful features. One site noted the system's ease of use as its best feature.

Items that could be improved include:

1) a better connector on the wind tunnel instrumentation box
2) the system defaulting to English units rather than SI units

3) the system uses a lot of memory and slows response and interferes with printing on occasions.
4) a few windows on the graphical user interface (GUI) do not contain enough digits in the display (all reports are fine it is just in the interface)
5) the list of previously calibrated test items needs to automatically sort in alpha/numeric order
6) the temperature/humidity probe cable should be one foot longer
7) in the "Report of Calibration" printout the display space next to "tolerance" and "comments" needs to be larger to allow for more information
8) the set point screen should have a dropdown menu of all models currently loaded (in alpha/numeric order) and having it automatically calculate the upper and lower tolerances would be a plus
9) The gray background on the prints is not helpful visually and it consumes significant amounts of ink.

In the area of additional comments,

1) System absolutely better than the previous version
2) Excellent support received from ORNL and AFMETCAL
3) The system is more consistently precise than the old one
4) The motor control board gets quite warm so please consider adding a fan to the instrumentation box to aid in reliability
5) One of the few really good modifications

6.0 Recommendations

General consensus of the user base is that the system is easy to operate, is reliable, and saves considerable time. Most of the troublesome or "could be improved" items are related to software/user interface issues. These concerns could be handled in an overall software system upgrade. It appears these items are in the "nice-to-have" category rather than a significant reliability or time inefficiency area. It seems that component failure is occurring but not at a high rate. It is recommended to have some spare parts available at a central location as a few of the instruments have six to eight week delivery times. If improved accuracy is required in the future, especially at the low flow velocities, the addition of a very low differential pressure transducer can help lower the uncertainty without significant hardware or software modifications.

7.0 Summary

Through a joint effort with the Department of Energy's Oak Ridge National Laboratory, the performance of PMEL wind tunnels were improved. The improvement consisted of new high accuracy sensors, automatic data acquisition, and a software-driven calibration process. As part of the wind tunnel upgrades, an uncertainty analysis was completed, laser Doppler velocimeter profiling was conducted to characterize the velocities at probe locations in the wind tunnel, and pitot tube calibrations of the wind tunnel were verified. The bench top wind tunnel accuracy and repeatability has been measured for nine prototype wind tunnel systems and valuable field experience has been gained with these wind tunnels at the PMELs. The uncertainty of the BTWT system was reduced significantly, as much as a factor of two to three, at the low flow velocity range. The automation reduced the time for a calibration by approximately 50% as estimated by the PMELs. The feedback from the field indicates the system does not take much start up time, is very easy to use and is user friendly, and has been reliable. Some suggested improvements were made by the users and recommendations were included in this summary report.

The initial goals set forth for this BTWT project were achieved and verified by field use in nine different locations around the world.

8.0 Acknowledgements

The authors would like to acknowledge the support and advice of our collaborators and sponsors at AFMTECAL, especially Dave Madden and Jim Baird. We also acknowledge the expertise of Dave Felde at ORNL and his instruction in the use and operation of the laser Doppler velocimeter system.

Appendix A - Evaluation of Uncertainty for the TSI Model 8390 Bench Top Wind Tunnel

This document outlines the formulation of uncertainty for the TSI Model 8390 Bench Top Wind Tunnel as directed by U.S. Air Force AFMETCAL through MIPR N9987000000048.

The mathematical relationship between the measurand (air velocity) and the input quantities upon which velocity depends may be derived through the application of Bernoulli's principle to the wind tunnel (Fig 1).

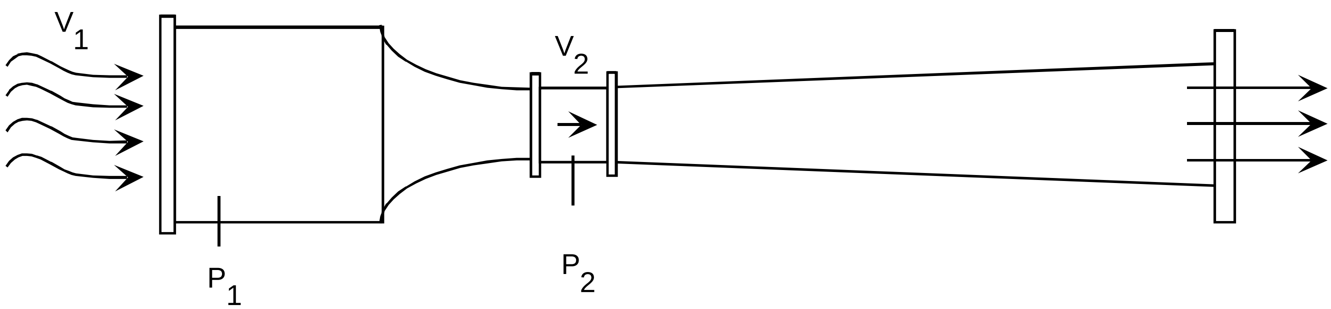

Fig 1. The TSI 8390 Bench Top Wind Tunnel.

Bernoulli's Equation:

$$\frac{P_1}{\rho_1} + \frac{V_1^2}{2} = \frac{P_2}{\rho_2} + \frac{V_2^2}{2} + LOSS$$

Where, LOSS is generated due to frictional losses with wind tunnel surfaces and entrance and exit effects. For the venturi configuration of the wind tunnel, these losses are traditionally lumped into a single discharge coefficient, C_0, which is functionally dependent with Reynolds number. The discharge coefficient is determined experimentally over the full range of velocity of the tunnel, by comparison against known airspeed measurements.

Bernoulli's Equation may be rewritten as:

$$\frac{P_1 - P_2}{\rho} \approx \frac{1}{2}\left[V_2^2 - V_1^2\right]$$

where, the density is averaged over the limited pressure drop occuring within the system between locations 1 and 2 and is evaluated as the average density between the two positions.

Continuity provides:

$$A_1 V_1 = A_2 V_2$$

where, A_1 and A_2 are the flow areas of the respective sections. Thus,

$$V_1 = V_2 \frac{A_2}{A_1} = V_2 \beta^2$$

where,

$$\beta = \frac{d_2}{D_1} \quad \beta^2 = \frac{A_2}{A_1}$$

For the general case TSI Model 8390, d_2=4.0 inches and D_1=11.825 inches.

Rearranging terms results in:

$$\frac{\Delta P}{\rho} = \frac{1}{2}\left[V_2^2 - \beta^4 V_2^2\right] = \frac{1}{2}\left[1 - \beta^4\right] V_2^2$$

$$V_2 = \frac{\sqrt{2}}{\sqrt{1-\beta^4}} \frac{1}{\sqrt{\rho}} \sqrt{\Delta P}$$

Density is functionally dependent upon the ambient pressure, the air temperature, and the relative humidity or moisture content of the air.

$$\rho = \rho_0 \frac{T_0}{T} \frac{P - 0.3783 e_w}{P_0}$$

where, T_0 and P_0 are reference conditions and P and T are actual conditions in units of torr and K. The vapor pressure of water, e_w, is also expressed in torr.

The vapor pressure of water may be calculated given the saturation vapor pressure of water at the prevailing conditions and the relative humidity:

$$e_w = 100(RH)(e_{ws})$$

where,

$$e_{ws} = \left[0.77 + 3.46x10^{-6}\,P\right]6.1121e^{\left[\frac{17.502(T-273.15)}{240.9+T-273.15}\right]}$$

Thus, using a known reference density at 273.15 K and 760 torr, the average density between points 1 and 2 within the wind tunnel may be calculated as:

$$\rho = 1.2929\,\frac{gms}{liter}\,\frac{(273.15K)}{T}\,\frac{(P-\frac{\Delta P}{2} - 0.3783x\left[100xRHx\left[0.77+3.46x10^{-6}(P-\frac{\Delta P}{2})\right]x6.1121e^{\left[\frac{17.502(T-275)}{240.9+T-273.15}\right]}\right]}{(760torr)}$$

where it is assumed the temperature and relative humidity of the air stream remain constant, and the average density of the air is equal to the density at ½ the differential pressure drop across the system.

Finally, this expression may be substituted into the Bernoulli derivation for velocity, providing the governing relationship between the measurand of this system (V) and the input quantities P, P, T, and RH:

$$V(P, dP, T, RH) := \frac{\sqrt{2}}{\sqrt{1-\beta^4}} \cdot \frac{\sqrt{dP}}{\sqrt{1.293\cdot\frac{gm}{liter}\cdot\left(\frac{273.15}{T}\right)\cdot\frac{\left[\left(P-\frac{dP}{2}\right) - .3783\cdot\frac{RH}{100}\cdot\left[.77\cdot torr + 3.46\cdot 10^{-6}\cdot\left(P-\frac{dP}{2}\right)\cdot\left[6.1121\cdot e^{\left[\frac{17.502\cdot(T-273.15)}{240.9+(T-273.15}\right.}\right.\right.\right.}{760\cdot torr}}}$$

This expression may be evaluated numerically to provide the sensitivity coefficients of the standard expression for measurement uncertainty, $u_c(v)$:

$$u_c^2(v) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)$$

or specifically,

$$u_c^2(v) = \left[\frac{\partial V}{\partial P}\right]^2 u_P^2 + \left[\frac{\partial V}{\partial \Delta P}\right]^2 u_{\Delta P}^2 + \left[\frac{\partial V}{\partial T}\right]^2 u_T^2 + \left[\frac{\partial V}{\partial RH}\right]^2 u_{RH}^2$$

To determine the worst case dependence, the sensitivity coefficients for each input parameter were determined numerically using MathCAD and plotted over the expected range of the respective input variable. The following plots indicate the sensitivity coefficient of each term, normalized in value as percent-of-measurand-reading, i.e.

$$normalized\_sensitivity\_coefficent = \frac{1}{V(x_i)}\left[\frac{\partial V}{\partial x_i}\right]x100$$

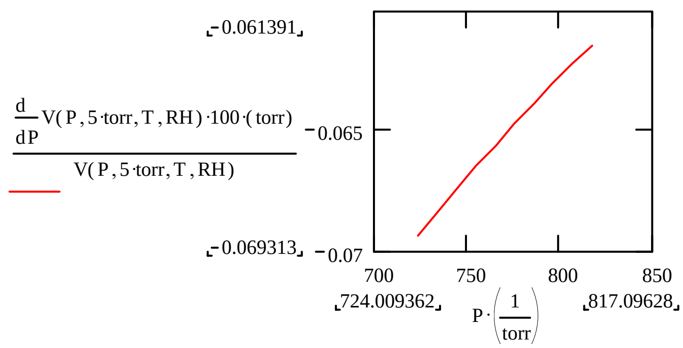

Figure 2. Absolute pressure normalized sensitivity coefficient (% rdg / torr).

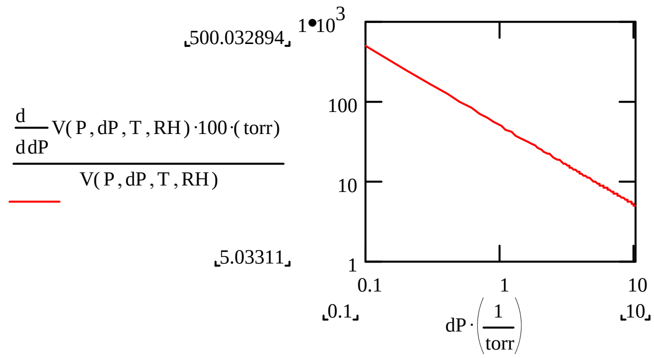

Fig 3. Differential pressure normalized sensitivity coefficient (% rdg / torr).

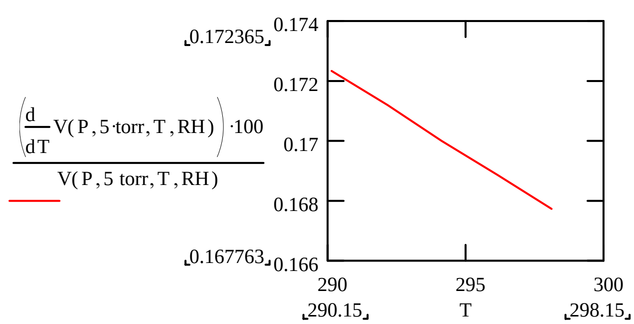

Fig 4. Temperature normalized sensitivity coefficient (% rdg / K).

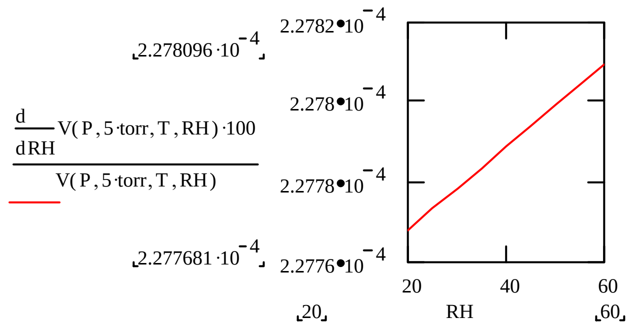

Fig 5. Relative humidity normalized sensitivity coefficient (% rdg / RH%).

This analysis provides direct evaluation of the sensitivity of the measurand to uncertainty of input variables.

For the model 8390AF, as upgraded, the instrumentation package is rated with the following:

Instrument	Manufacturer's Specification	As Calibrated
Relative Humidity	2% RH	4% RH
Temperature	0.3 deg C	0.1 deg C
Absolute Pressure	0.05% FS	0.15% Rdg
Differential Pressure	0.01% FS	0.04% Rdg

Relying solely on the manufacturer's specification for the wind tunnel instrumentation would result in the following uncertainty throughout the airspeed ranges of the wind tunnel (Figure 6)

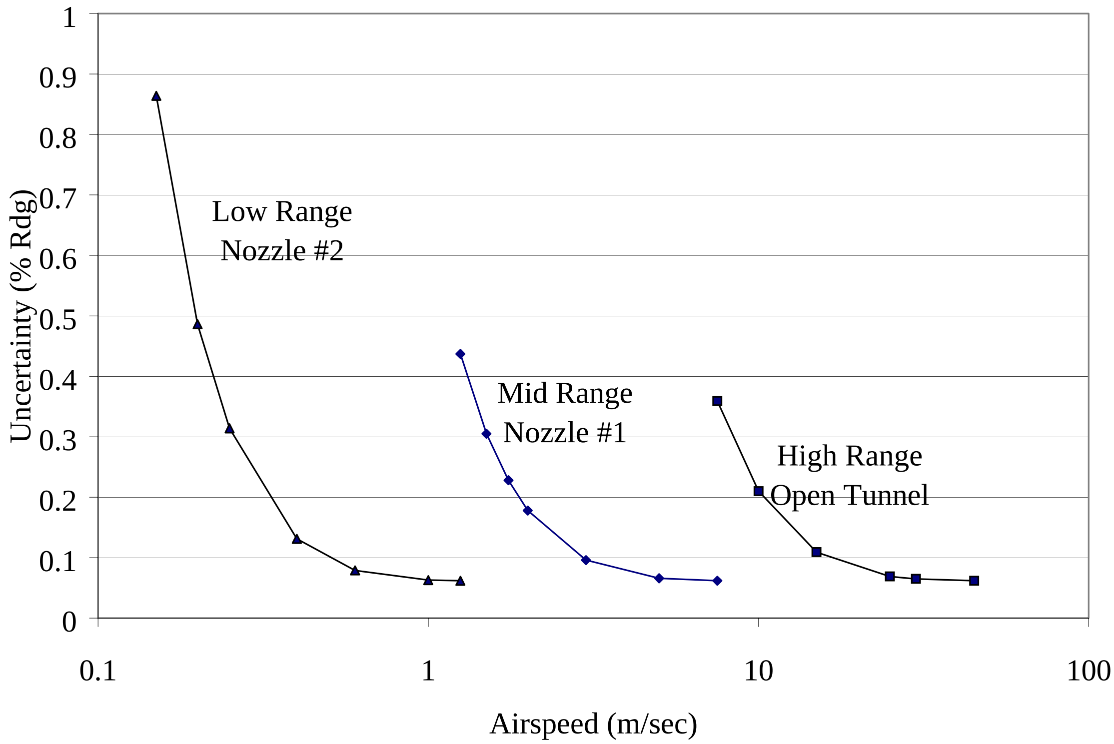

Figure 6. Static uncertaintly using full capabilities of WTIP instrumentation.

As would be expected, the maximum static uncertainty of the wind tunnel system will occur at the low end of each airspeed range, where the uncertainty component of the differential pressure cell generates a significant component of the overall uncertainty.

In actual practice, however, the P cell of the wind tunnel instrumentation package actually calibrated much better than manufacturer's specification at the low end, i.e. to within 0.04% of reading as opposed to .01% of full scale using a cross-floated dead weight testing scheme to provide accurate standard differential pressures from 0 to 5 torr. Currently, however, field standards for differential pressure (i.e. Hooke Gages) do not provide for calibration to this level of uncertainty. Calibration with these field standards provides a 0.005 torr uncertainty in the differential pressure measurement, which is an uncertainty greater than the manufacturer's specification for the differential pressure unit. Using this higher uncertainty value for the differential pressure measurement results in an increase in static uncertainty throughout the wind tunnel's range of use, as indicated in Figure 7.

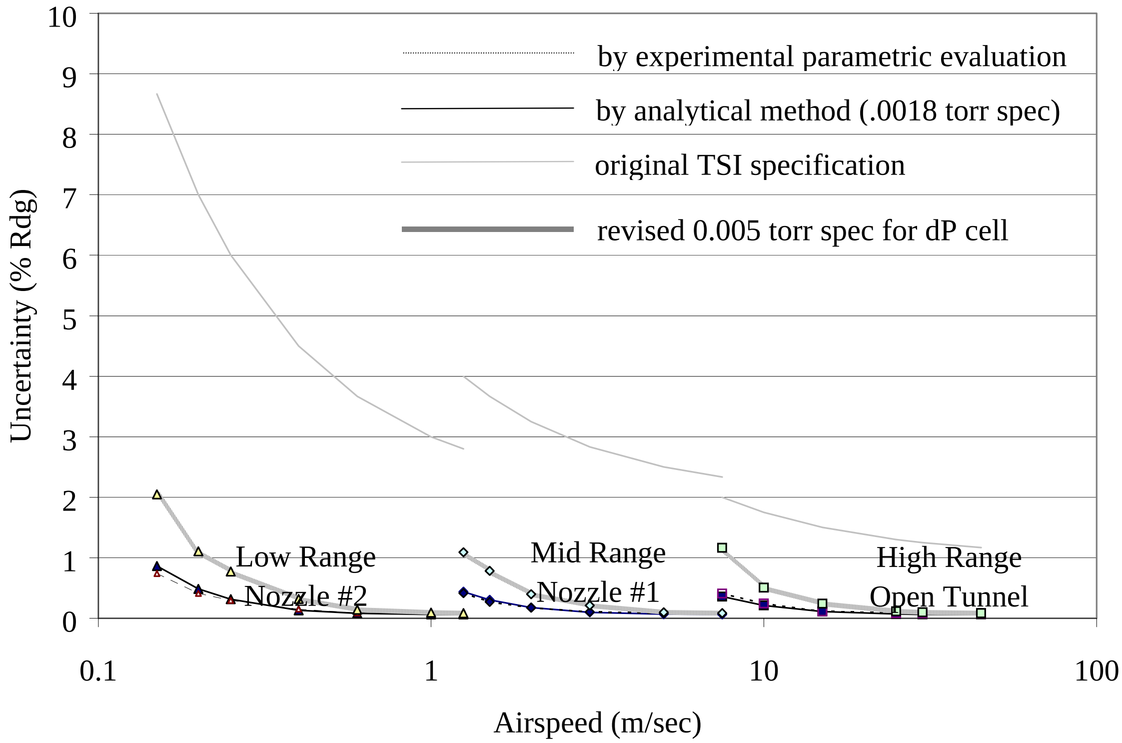

Figure 7. Static uncertainty of wind tunnel package based on manufacturer specification of instruments (experimental and analytical curves) and based on calibration of the differential pressure unit using field standard Hooke Gages (revised 0.005 torr curve). Note, overall manufacturer's uncertainty for the wind tunnel (original TSI specification).

Overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

Calibrated Range	Uncertainty	Nozzle Plate
< 0.3 m/sec (60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60 - 250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250- 600 fpm)	1.25% of reading	#1
3 to 7.5 m/s (600 - 1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000 -9000 fpm)	1.0% of reading	Open

Appendix B – Individual Calibration of Each Wind Tunnel

The nine wind tunnels were labeled AF01, AF02… AF09. The wind tunnels were sent to the following PMEL locations.

PMEL Location	Wind Tunnel Label
AFMETCAL	AF01
Robins AFB	AF02
Tinker AFB	AF03
Hill AFB	AF04
Kadena AB	AF05
Feltwell AB	AF06
Elmendorf AFB	AF07
Vandenberg AFB	AF08
Cape Canaverel AFS	AF09

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Building 3500 Room 9
Oak Ridge, TN 37831

UT-BATTELLE

Report of Calibration - November 4, 2000

Instrument Identification: WTIP 2000, S/N AF01
Instrument Serial: AF01
Descriptor: TSI Model 8390 Wind Tunnel S/N 169
Span: 0.15 - 45 m/sec
Uncertainty: See attached chart

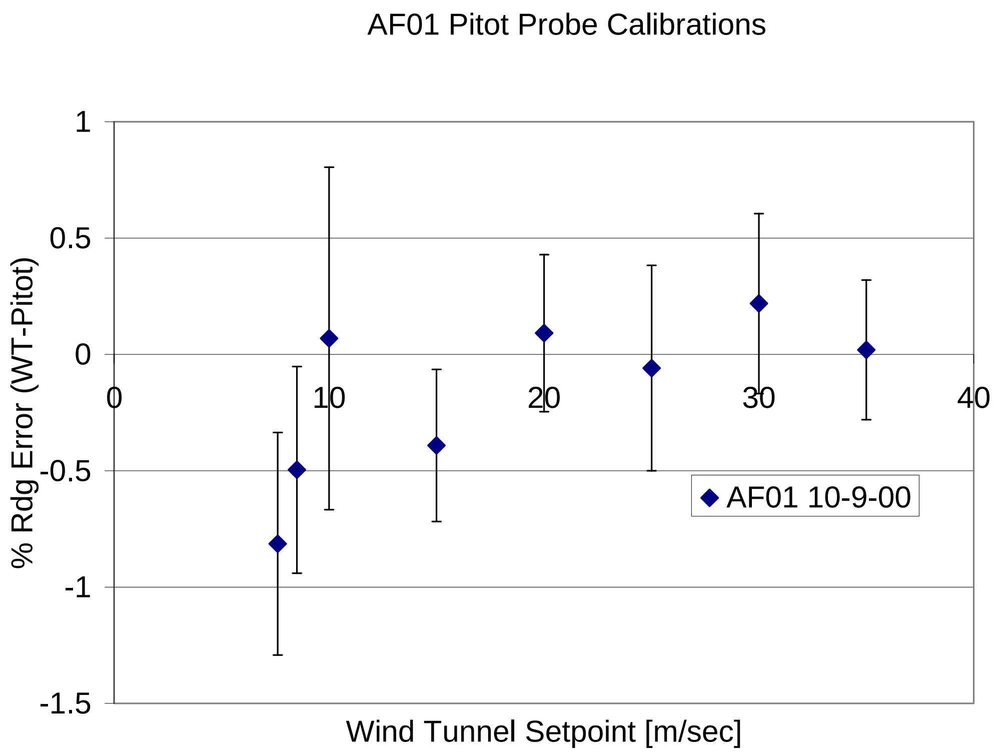
Calibration Conditions: 14.25 psia, 23 deg C, 36% RH
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

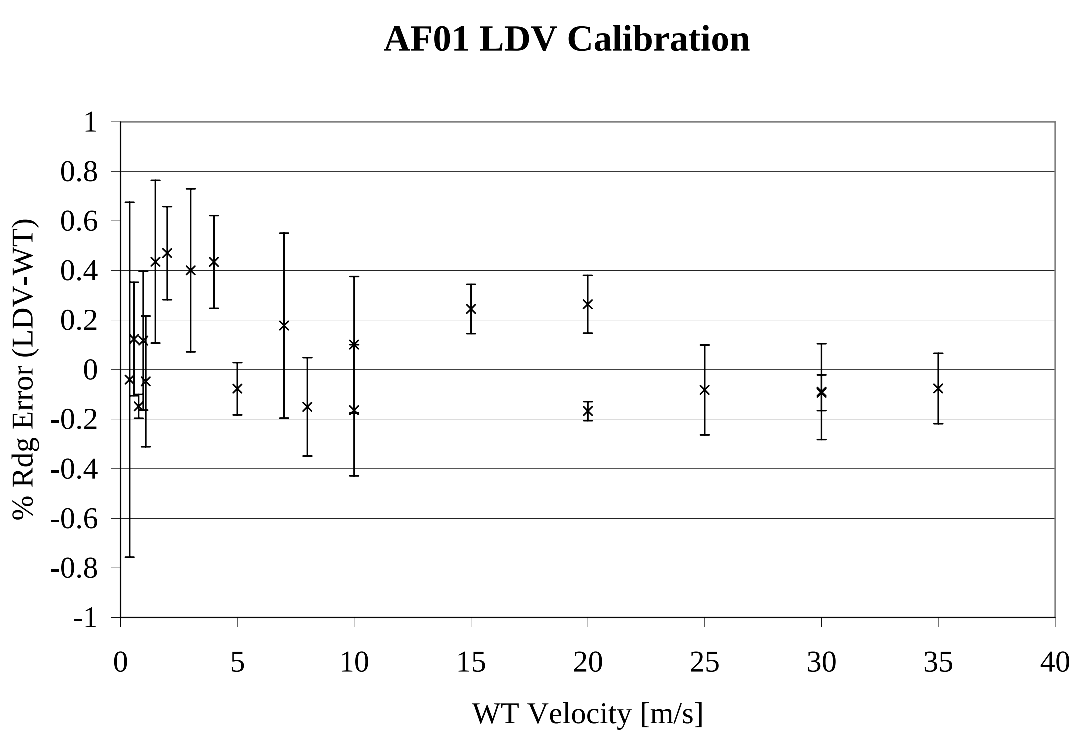
Wind Tunn Config	Standard Value	T.I. Indication	Error (STD-TI)	% Error (% Rdg)	Poly Fit	
	(m/sec)	(m/sec)	(m/sec)			
Nozzle #2	0.3863	0.3865	0.000	-0.050	a:	-2.1004E-03
Nozzle #2	0.5837	0.5831	0.001	0.112	b:	9.6408E-01
Nozzle #2	0.7799	0.7811	-0.001	-0.158	c:	1.8720E-02
Nozzle #2	0.9818	0.9807	0.001	0.105		
Nozzle #2	1.0804	1.0811	-0.001	-0.058		
Nozzle #1	1.5065	1.5002	0.006	0.419	a:	0.0000E+00
Nozzle #1	2.0092	2.0001	0.009	0.453	b:	1.0000E+00
Nozzle #1	3.0121	3.0005	0.012	0.384	c:	0.0000E+00
Nozzle #1	4.0172	4.0004	0.017	0.418		
Nozzle #1	4.9960	5.0003	-0.004	-0.087		
Nozzle #1	7.0121	7.0005	0.012	0.165		
Open	7.9877	8.0004	-0.013	-0.159	a:	0.0000E+00
Open	9.9796	9.9969	-0.017	-0.173	b:	1.0000E+00
Open	10.0089	10.0000	0.009	0.089	c:	0.0000E+00
Open	15.0355	15.0007	0.035	0.231		
Open	19.9650	20.0002	-0.035	-0.176		
Open	20.0491	19.9991	0.050	0.250		
Open	24.9778	25.0007	-0.023	-0.092		
Open	29.9710	30.0018	-0.031	-0.103		
Open	29.9749	30.0044	-0.029	-0.098		
Open	34.9700	35.0001	-0.030	-0.086		

Comments:
Indicated velocities are standardized to indicate standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated polynomial fit coefficients. These coefficients are implemented in the wind tunnel software; no additional correction is required by the user.

Corrected Indication=a+b(indication)+c(indication)^2

Instrumentation and Controls Metrology Laboratory (ICML) certifies that the instrument listed was calibrated using standards whose accuracies are traceable to the National Institute of Standards and Technology (NIST) or have been derived from accepted val





Overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

Calibrated Range	Uncertainty	Nozzle Plate
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0.3 to 1.25 m/s (60 - 250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250- 600 fpm)	1.25% of reading	#1
3 to 7.5 m/s (600 - 1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000 -9000 fpm)	1.0% of reading	Open

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UT-BATTELLE

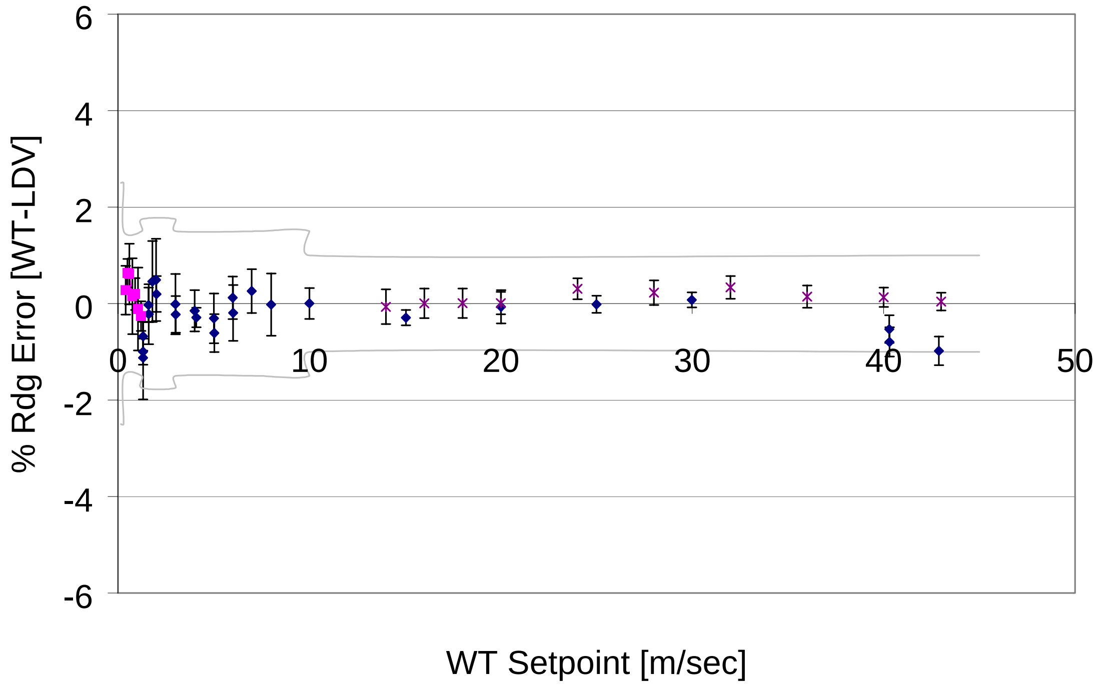
Report of Calibration - March 30, 2001

Instrument Identification: WTIP 2000, S/N AF02
Instrument Serial: AF02
Descriptor: TSI Model 8390 Wind Tunnel
Span: 0.15 - 45 m/sec
Uncertainty: See attached chart

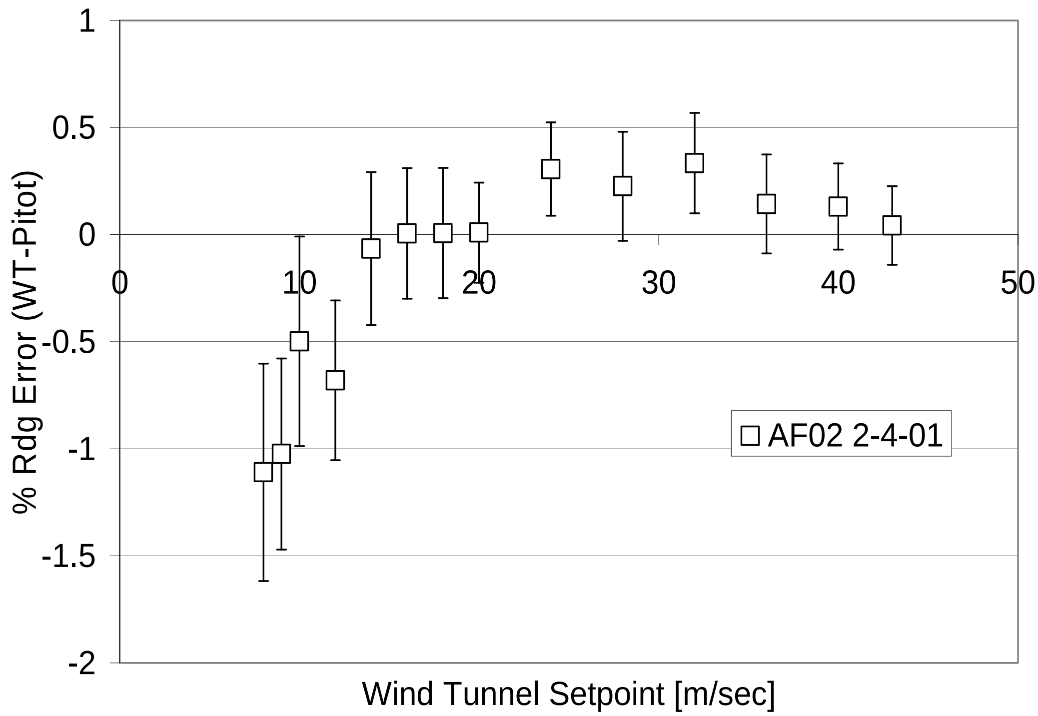
Calibration Conditions: 14.25 psia, 23 deg C, 36% RH
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	Standard Value (m/sec)	T.I. Indication (m/sec)	Error (STD-TI) (m/sec)	% Error (% Rdg)
Nozzle #2	0.4000	0.3989	0.001	0.278
Nozzle #2	0.5000	0.4969	0.003	0.633
Nozzle #2	0.6001	0.5964	0.004	0.612
Nozzle #2	0.7500	0.7489	0.001	0.152
Nozzle #2	0.9000	0.8982	0.002	0.198
Nozzle #2	1.0501	1.0513	-0.001	-0.113
Nozzle #2	1.1999	1.2030	-0.003	-0.260
Nozzle #1	1.3000	1.3146	-0.015	-1.122
Nozzle #1	1.2992	1.3121	-0.013	-0.996
Nozzle #1	1.6010	1.6014	0.000	-0.029
Nozzle #1	2.0109	2.0069	0.004	0.198
Nozzle #1	3.0094	3.0161	-0.007	-0.226
Nozzle #1	4.0747	4.0865	-0.012	-0.289
Nozzle #1	5.0008	5.0313	-0.031	-0.611
Nozzle #1	6.0010	5.9938	0.007	0.120
Nozzle #1	7.0005	6.9824	0.018	0.259
Open	7.9991	8.0008	-0.002	-0.022
Open	9.9997	9.9995	0.000	0.003
Open	13.9977	14.0069	-0.009	-0.065
Open	16.000	15.999	0.001	0.005
Open	18.000	17.998	0.001	0.007
Open	20.003	20.001	0.002	0.010
Open	24.003	23.930	0.073	0.306
Open	28.000	27.936	0.063	0.226
Open	32.000	31.893	0.107	0.334
Open	36.004	35.953	0.052	0.143
Open	39.995	39.942	0.052	0.131
Open	42.998	42.979	0.018	0.043

Instrumentation and Controls Metrology Laboratory (ICML) certifies that the instrument listed was calibrated using standards whose accuracies are traceable to the National Institute of Standards and Technology (NIST) or have been derived from accepted values of natural physical constants, or by the ratio type of self calibration. This report shall not be reproduced except in full without written approval of ICML.



AF02 Pitot Probe Calibrations



Overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

Calibrated Range	Uncertainty	Nozzle Plate
0.15 to 0.3 m/s (30 – 60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60 - 250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250- 600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600 - 1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000 -9000 fpm)	1.0% of reading	Open

Oak Ridge National Laboratory
Instrumentation and Controls Division
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P.O. Box 2008 MS 6004
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UT-BATTELLE

Report of Calibration - July 9, 2001

Instrument Identification: WTIP 2000, S/N AF03
Instrument Serial: AF03
Descriptor: TSI Model 8390 Wind Tunnel
Span: 0.15 - 45 m/sec
Uncertainty: See attached chart

Calibration Conditions: 14.27 psia, 27 deg C, 42% RH
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	Standard Value (m/sec)	T.I. Indication (m/sec)	Error (TI-STD) (m/sec)	% Error (% Rdg)			Poly Fit
Nozzle #2	0.152136	0.152184	0.000	0.031		a:	0.0000
Nozzle #2	0.202164	0.20208	0.000	-0.041		b:	1.0000
Nozzle #2	0.305584	0.302008	-0.004	-1.184		c:	0.0000
Nozzle #2	0.399486	0.402169	0.003	0.667			
Nozzle #2	0.499453	0.502659	0.003	0.638			
Nozzle #2	1.113905	1.111535	-0.002	-0.213			
Nozzle #2	1.263124	1.265193	0.002	0.164			
Nozzle #1	1.3056	1.2993	-0.006	-0.485		a:	0.039565
Nozzle #1	1.5003	1.4943	-0.006	-0.402		b:	0.96374
Nozzle #1	1.7498	1.7384	-0.011	-0.656		c:	0.004049
Nozzle #1	2.462	2.4741	0.012	0.489			
Nozzle #1	2.9658	2.9671	0.001	0.044			
Nozzle #1	3.4598	3.4624	0.003	0.075			
Nozzle #1	3.95	3.9585	0.008	0.215			
Nozzle #1	4.4652	4.4582	-0.007	-0.157			
Nozzle #1	4.9752	4.9596	-0.016	-0.315			
Nozzle #1	5.4538	5.4619	0.008	0.148			
Nozzle #1	5.9829	5.968	-0.015	-0.250			
Nozzle #1	6.9709	6.9823	0.011	0.163			
Open	8.0315	7.9996	-0.032	-0.399		a:	0.0000E+00
Open	9.0423	8.9994	-0.043	-0.477		b:	1.0000E+00
Open	10.0253	9.9997	-0.026	-0.256		c:	0.0000E+00
Open	11.9608	12.0001	0.039	0.327			
Open	14.9537	14.9998	0.046	0.307			
Open	19.9352	20.0024	0.067	0.336			
Open	24.9309	24.9983	0.067	0.270			
Open	29.8343	29.9992	0.165	0.550			
Open	39.9749	40.0044	0.029	0.074			

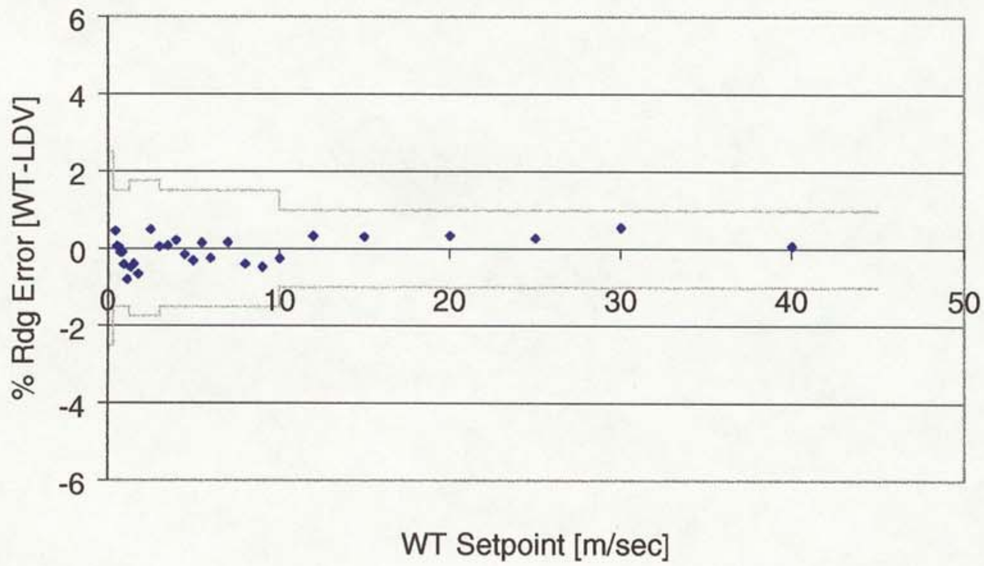
Comments:
Indicated velocities are standardized to indicated standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated polynomial fit coefficients. These coefficients are implemented in the wind tunnel software, no

The overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by the laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

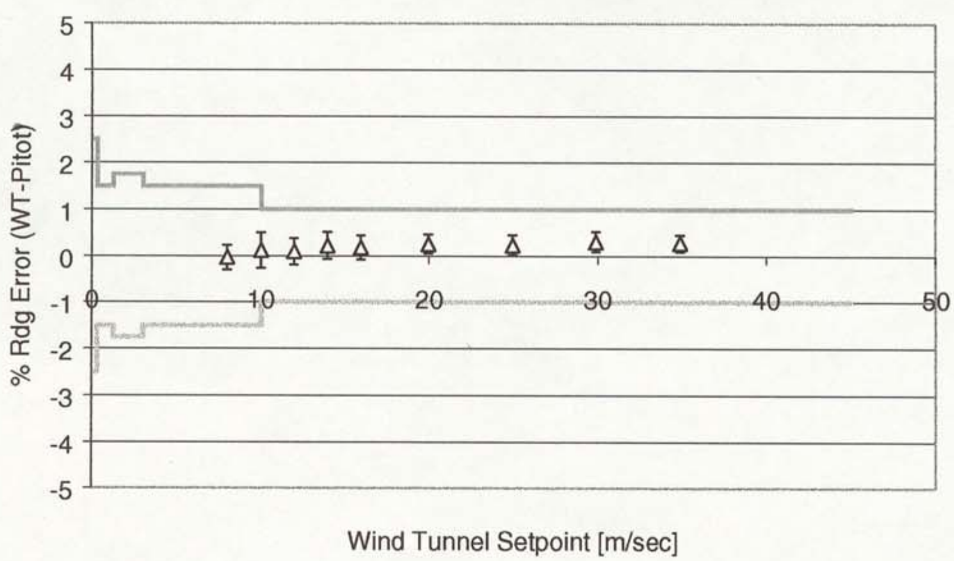
OVERALL UNCERTAINTY OF BENCH TOP WIND TUNNEL

CALIBRATED RANGE	WTAP UNCERTAINTY	NOZZLE PLATE
0.15 to 0.3 m/s (30-60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60-250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250-600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600-1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000-9000 fpm)	1.0% of reading	Open

AF03 LDV Calibration



AF03 Pitot Probe Calibration



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Instrumentation and Controls Division
Technical Support & Management Systems
P.O. Box 2008 MS 6004
Building 3500 Room 9
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Report of Calibration - November 29-30, 2001

Instrument Identification: WTIP 2000, S/N AF04
Instrument Serial: AF04
Descriptor: TSI Model 8390 Wind Tunnel
Span: 0.15 - 45 m/sec
Uncertainty: See attached chart

Calibration Conditions: 14.27 psia, 27 deg C, 42% RH
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	Standard Value (m/sec)	T.I. Indication (m/sec)	Error (TI-STD) (m/sec)	% Error (% Rdg)		Poly Fit	
Nozzle #2	0.152136	0.152184	0.000	0.031		a:	0.00295344
Nozzle #2	0.202164	0.20208	0.000	-0.041		b:	0.99281539
Nozzle #2	0.305584	0.302008	-0.004	-1.184		c:	0.01364104
Nozzle #2	0.399486	0.402169	0.003	0.667			
Nozzle #2	0.499453	0.502659	0.003	0.638			
Nozzle #2	0.70566	0.70463	-0.001	-0.146			
Nozzle #2	0.908443	0.907498	-0.001	-0.104			
Nozzle #2	1.113905	1.111535	-0.002	-0.213			
Nozzle #2	1.263124	1.265193	0.002	0.164			
Nozzle #1	1.305908	1.308087	0.002	0.167		a:	0.06039466
Nozzle #1	1.495187	1.501431	0.006	0.416		b:	0.95271718
Nozzle #1	2.001102	1.986941	-0.014	-0.713		c:	0.00535297
Nozzle #1	2.962396	2.966313	0.004	0.132			
Nozzle #1	4.946228	4.957898	0.012	0.235			
Nozzle #1	5.984552	5.969591	-0.015	-0.251			
Nozzle #1	6.986864	6.991976	0.005	0.073			
Open	8.037404	7.999672	-0.038	-0.472		a:	0.0000E+00
Open	14.98814	14.99994	0.012	0.079		b:	1.0000E+00
Open	19.94572	20.00172	0.056	0.280		c:	0.0000E+00
Open	24.85458	24.99738	0.143	0.571			
Open	29.85396	29.998	0.144	0.480			

Comments:
Indicated velocities are standardized to indicated standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated polynomial fit coefficients. These coefficients are implemented in the wind tunnel software, no additional correction is required by the user.

ORNL Metrology Laboratory (ORNLML) certifies that the instrument listed was calibrated using standards whose accuracies are traceable to the National Institute of Standards and Technology (NIST) or have been derived from accepted values of natural physical constants, or by the ratio type of self calibration.
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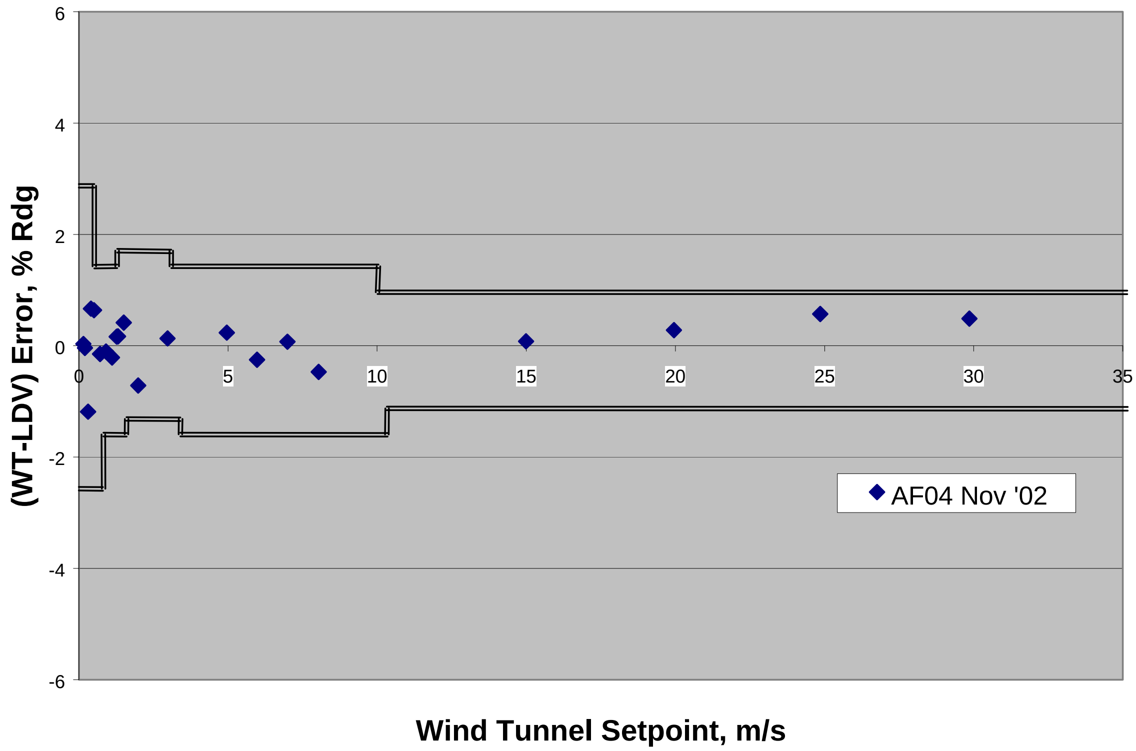
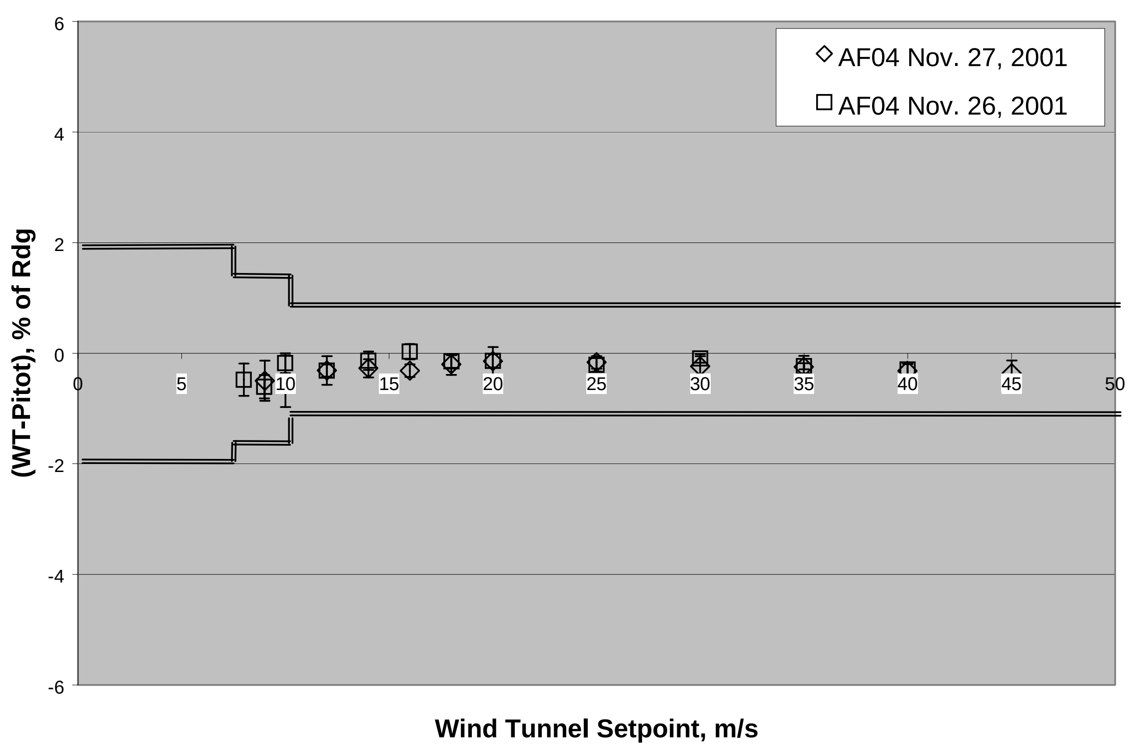
AF04 LDV CALIBRATION



AF04 Pitot Tube Calibration



The overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by the laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

OVERALL UNCERTAINTY OF BENCH TOP WIND TUNNEL

CALIBRATED RANGE	WTAP UNCERTAINTY	NOZZLE PLATE
0.15 to 0.3 m/s (30-60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60-250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250-600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600-1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000-9000 fpm)	1.0% of reading	Open

Oak Ridge National Laboratory
Instrumentation and Controls Division
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Oak Ridge, TN 37831

UT-BATTELLE

Report of Calibration - April 2002

Instrument Identification: WTIP 2000, S/N AF05
Instrument Serial: AF05
Descriptor: TSI Model 8390 Wind Tunnel
Span: 0.15 - 45 m/sec
Uncertainty: See attached chart

Calibration Conditions: 14.32 psia, 27 deg C, 47% RH
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	Standard Value (m/sec)	T.I. Indication (m/sec)	Error (TI-STD) (m/sec)	% Error (% Rdg)			Poly Fit
Nozzle #2	0.156693	0.154803	-0.002	-1.221		a:	-0.004193
Nozzle #2	0.1956	0.197001	0.001	0.711		b:	1.01098
Nozzle #2	0.196311	0.194988	-0.001	-0.679		c:	-0.023272
Nozzle #2	0.297091	0.295009	-0.002	-0.706			
Nozzle #2	0.391517	0.394224	0.003	0.687			
Nozzle #2	0.3936	0.396488	0.003	0.728			
Nozzle #2	0.394485	0.394282	0.000	-0.051			
Nozzle #2	0.491817	0.492794	0.001	0.198			
Nozzle #2	0.686793	0.687705	0.001	0.133			
Nozzle #2	0.6924	0.69218	0.000	-0.032			
Nozzle #2	0.882888	0.879688	-0.003	-0.364			
Nozzle #2	0.988	0.983852	-0.004	-0.422			
Nozzle #2	1.067168	1.068919	0.002	0.164			
Nozzle #2	1.160026	1.162455	0.002	0.209			
Nozzle #1	1.293431	1.280417	-0.013	-1.016		a:	0.01540897
Nozzle #1	1.268	1.288839	0.021	1.617		b:	0.97718228
Nozzle #1	1.598906	1.585153	-0.014	-0.868		c:	0.00176556
Nozzle #1	1.993915	1.989548	-0.004	-0.220			
Nozzle #1	2.49182	2.494897	0.003	0.123			
Nozzle #1	2.95	2.963167	0.013	0.444			
Nozzle #1	2.995282	2.996376	0.001	0.036			
Nozzle #1	4.00174	3.995814	-0.006	-0.148			
Nozzle #1	4.918	4.946479	0.028	0.576			
Nozzle #1	5.006927	4.987235	-0.020	-0.395			
Nozzle #1	5.993414	5.972616	-0.021	-0.348			
Nozzle #1	6.924	6.943175	0.019	0.276			
Nozzle #1	6.960473	6.952191	-0.008	-0.119			
OPEN	8.072646	7.999784	-0.073	-0.911		a:	0.0000
OPEN	9.087431	8.999502	-0.088	-0.977		b:	1.0000
OPEN	10.09489	9.998001	-0.097	-0.969		c:	0.0000
OPEN	15.0937	15.00116	-0.093	-0.617			
OPEN	20.06355	20.00226	-0.061	-0.306			
OPEN	25.03409	25.0035	-0.031	-0.122			
OPEN	10.05484	9.996381	-0.058	-0.585			

Comments:
Indicated velocities are standardized to indicated standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated polynomial fit coefficients. These coefficients are implemented in the wind tunnel software, no additional correction is required by the user.

ORNL Metrology Laboratory (ORNLML) certifies that the instrument listed was calibrated using standards whose accuracies are traceable to the National Institute of Standards and Technology (NIST) or have been derived from accepted values of natural physical constants, or by the ratio type of self calibration.
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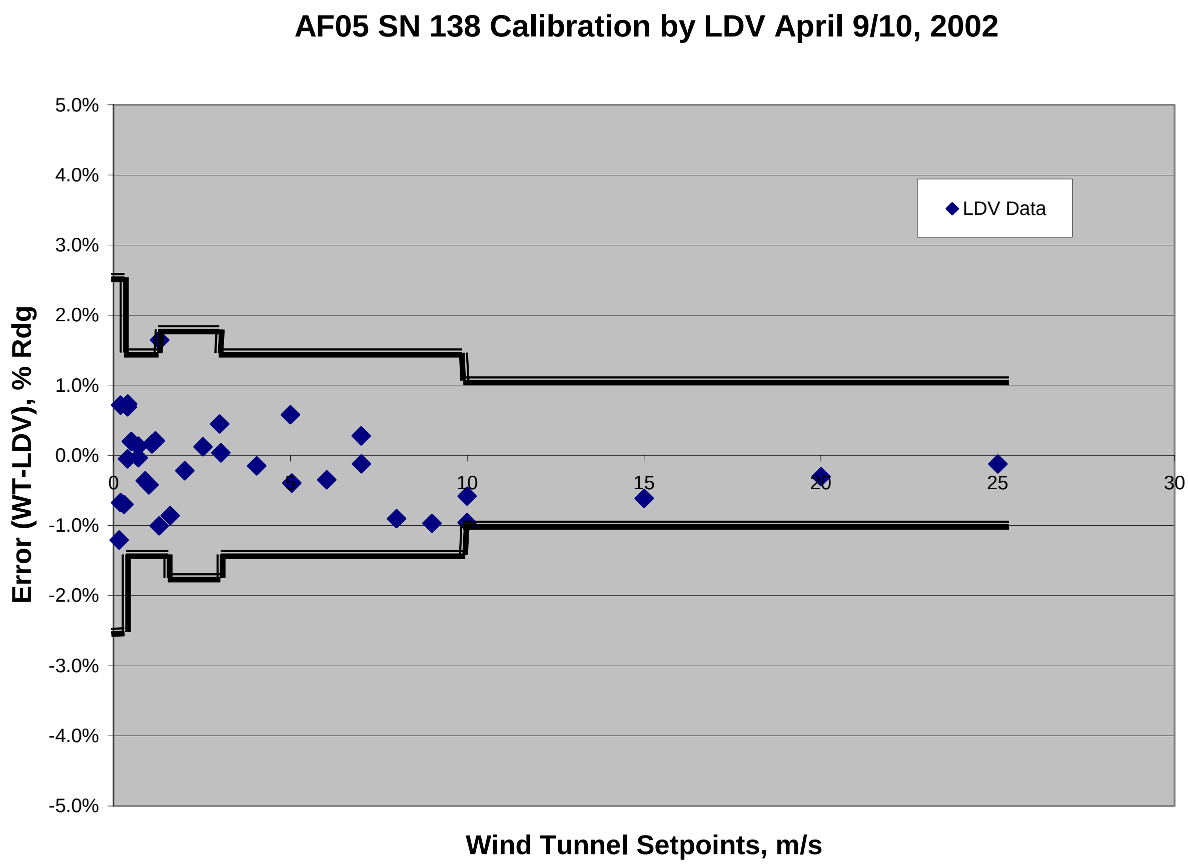
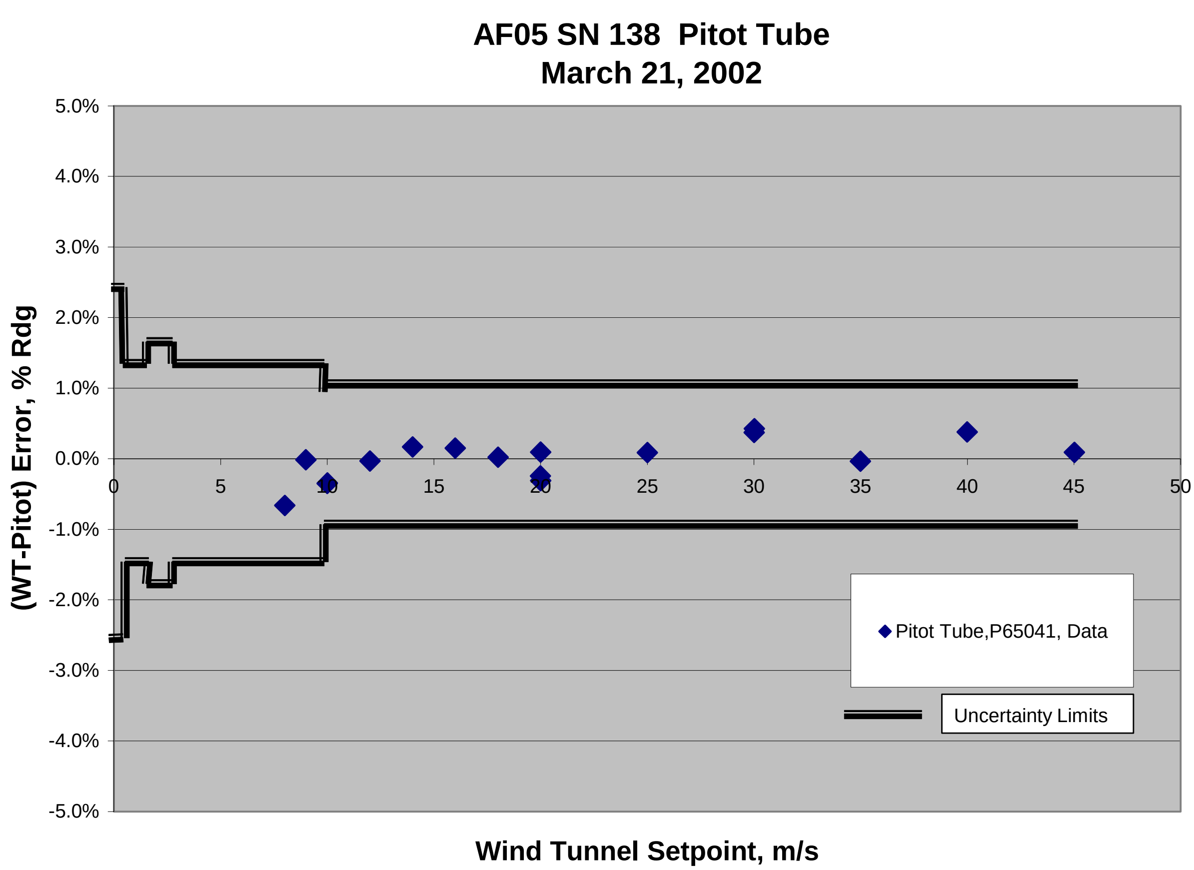

AF05 SN 138 Calibration by LDV April 9/10, 2002
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
-1.0%
-2.0%
-3.0%
-4.0%
-5.0%
0
5
10
15
20
25
30
Error (WT-LDV), % Rdg
Wind Tunnel Setpoints, m/s
LDV Data


AF05 SN 138 Pitot Tube
March 21, 2002
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
-1.0%
-2.0%
-3.0%
-4.0%
-5.0%
0
5
10
15
20
25
30
35
40
45
50
(WT-Pitot) Error, % Rdg
Wind Tunnel Setpoint, m/s
Pitot Tube,P65041, Data
Uncertainty Limits

Overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

Calibrated Range	Uncertainty	Nozzle Plate
0.15 to 0.3 m/s (30 – 60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60 - 250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250- 600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600 - 1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000 -9000 fpm)	1.0% of reading	Open

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UT-BATTELLE

Report of Calibration - September to May 2002/2003

Instrument Identification: WTIP 2000, S/N AF06

Instrument Serial: AF06

Descriptor: TSI Model 8390 Wind Tunnel

Span: 0.15 - 45 m/sec

Uncertainty: See attached chart

Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	**Standard Value (m/sec)**	**T.I. Indication (m/sec)**	**Error (TI-STD) (m/sec)**	**% Error (% Rdg)**		**Poly Fit**	
Nozzle #2	0.201547	0.199677	-0.002	-0.937		a:	-0.018353
Nozzle #2	0.307234	0.306238	-0.001	-0.326		b:	1.106741
Nozzle #2	0.309919	0.306212	-0.004	-1.211		c:	-0.082296
Nozzle #2	0.40222	0.411159	0.009	2.174			
Nozzle #2	0.511269	0.514449	0.003	0.618			
Nozzle #2	0.516347	0.514423	-0.002	-0.374			
Nozzle #2	0.66708	0.666285	-0.001	-0.119			
Nozzle #2	0.815644	0.814179	-0.001	-0.180			
Nozzle #2	1.010913	1.006379	-0.005	-0.451			
Nozzle #2	1.18744	1.190613	0.003	0.266			
Nozzle #1	1.296592	1.300068	0.003	0.267		a:	0.0000E+00
Nozzle #1	1.617272	1.618107	0.001	0.052		b:	1.0000E+00
Nozzle #1	2.003033	1.99974	-0.003	-0.165		c:	0.0000E+00
Nozzle #1	2.010815	2.00012	-0.011	-0.535			
Nozzle #1	2.962812	2.999961	0.037	1.238			
Nozzle #1	3.01511	2.999729	-0.015	-0.513			
Nozzle #1	3.999004	4.001659	0.003	0.066			
Nozzle #1	5.501448	5.499489	-0.002	-0.036			
Nozzle #1	6.961792	6.999423	0.038	0.538			
Nozzle #1	6.986864	6.991976	0.005	0.073			
Open	8.087833	7.998004	-0.090	-1.123		a:	0.0000E+00
Open	10.07861	10.0004	-0.078	-0.782		b:	1.0000E+00
Open	15.05654	15.00111	-0.055	-0.370		c:	0.0000E+00
Open	20.07777	20.00439	-0.073	-0.367			

Comments:

Indicated velocities are standardized to indicate standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated
polynomial fit coefficients. These coefficients are implemented in the wind tunnel software, no
additional correction is required by the user.

ORNL Metrology Laboratory (ORNLML) certifies that the instrument listed was
calibrated using standards whose accuracies are traceable to the
National Institute of Standards and Technology (NIST) or have been derived from
accepted values of natural physical constants, or by the ratio type of self calibration.
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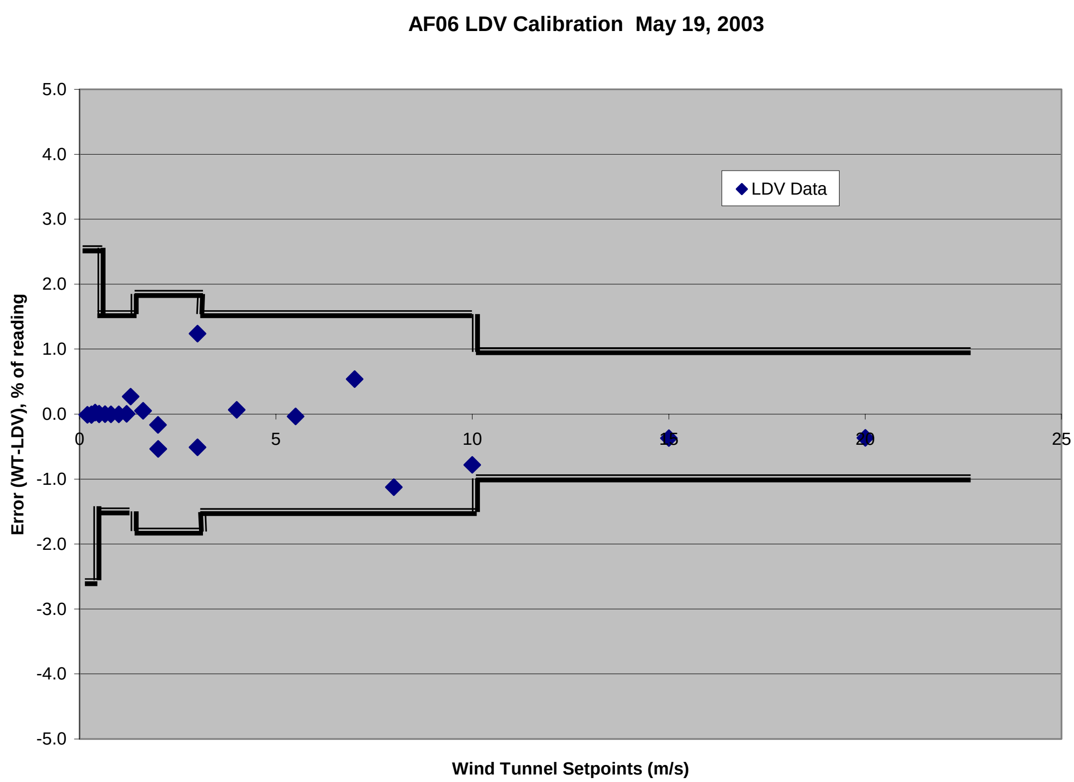
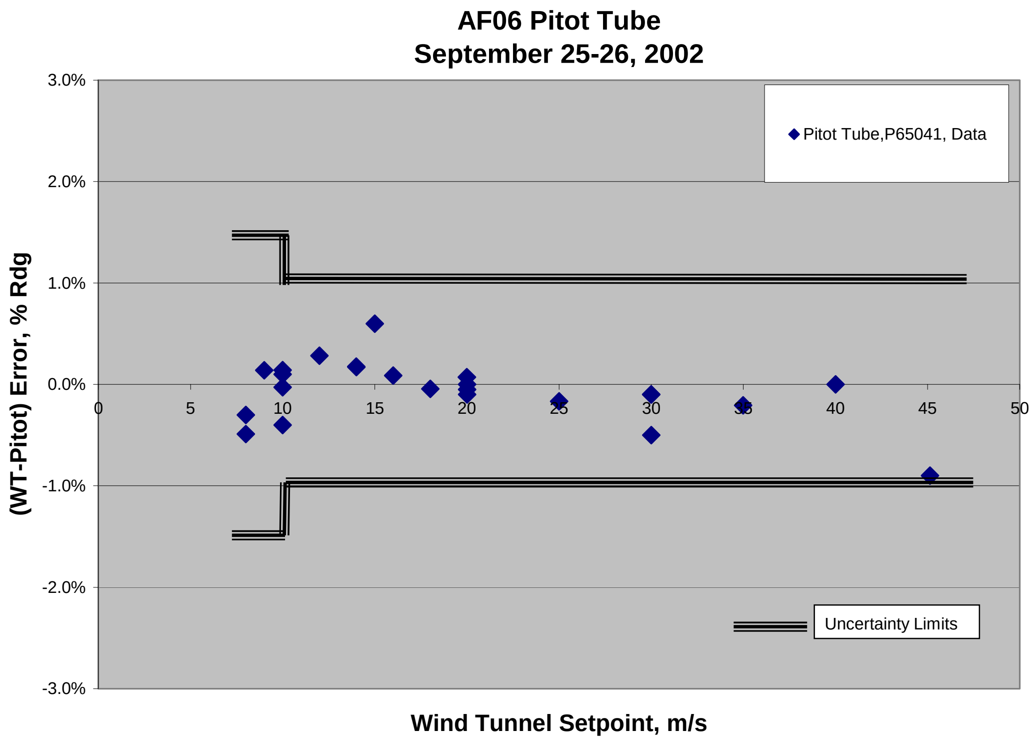




Overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

Calibrated Range	Uncertainty	Nozzle Plate
0.15 to 0.3 m/s (30 – 60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60 - 250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250- 600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600 - 1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000 -9000 fpm)	1.0% of reading	Open

OAK RIDGE NATIONAL LABORATORY
ENGINEERING SCIENCE AND TECHNOLOGY DIVISION

Report of Calibration - September 19-22, 2003

Instrument Identification: WTIP 2000, S/N AF07
Instrument Serial: AF07
Descriptor: TSI Model 8390 Wind Tunnel
Span: 0.15 - 45 m/sec
Uncertainty: See attached chart

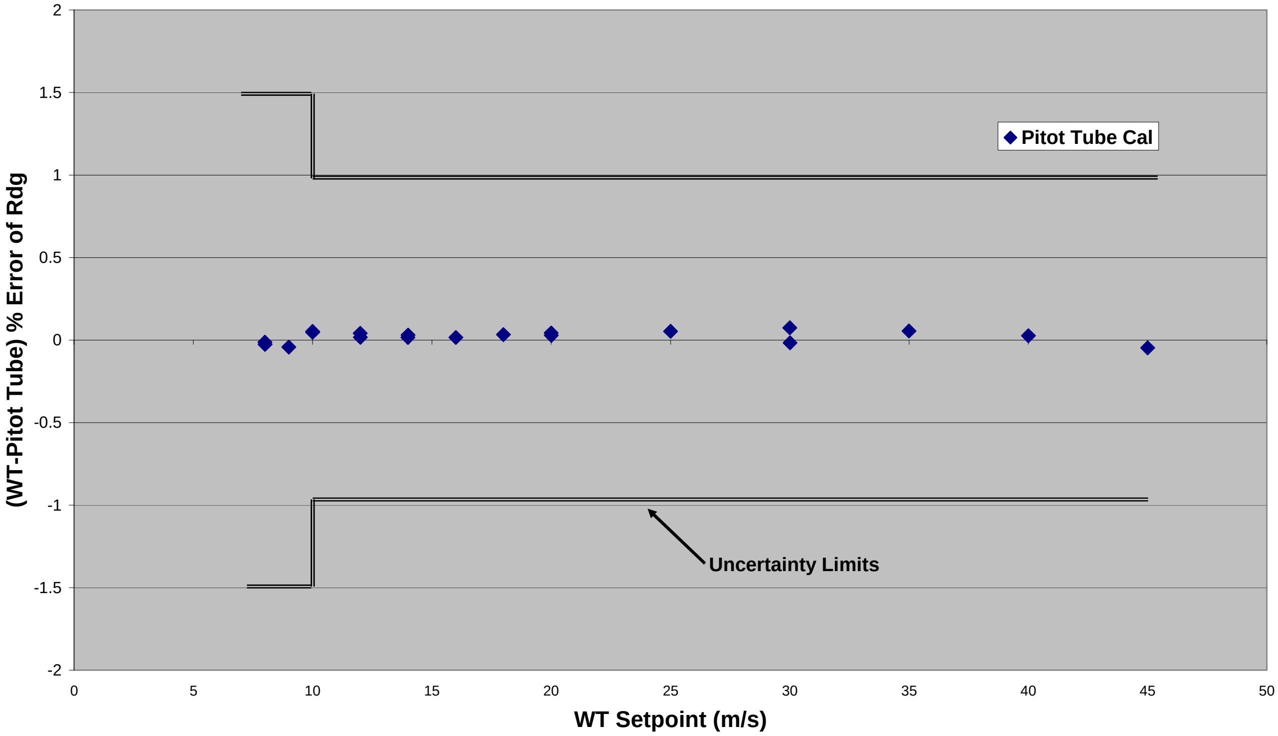
Calibration Conditions: 14.16 psia, 23 deg C, 58% RH
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	Standard Value (m/sec)	T.I. Indication (m/sec)	Error (TI-STD) (m/sec)	% Error (% Rdg)		Poly Fit	
Nozzle #2	0.145133	0.146937	0.002	1.227		a:	-0.01173
Nozzle #2	0.197933	0.195839	-0.002	-1.069		b:	1.067862
Nozzle #2	0.250427	0.251171	0.001	0.296		c:	-0.04314
Nozzle #2	0.302651	0.297356	-0.005	-1.781			
Nozzle #2	0.406198	0.409491	0.003	0.804			
Nozzle #2	0.508598	0.513087	0.004	0.875			
Nozzle #2	0.710056	0.710061	0.000	0.001			
Nozzle #2	0.858334	0.852956	-0.005	-0.631			
Nozzle #2	1.003704	1.005633	0.002	0.192			
Nozzle #2	1.241324	1.241827	0.001	0.041			
Nozzle #1	1.496659	1.513546	0.017	1.116		a:	-0.02177
Nozzle #1	2.017843	2.000391	-0.017	-0.872		b:	1.014676
Nozzle #1	3.049385	3.03817	-0.011	-0.369		c:	-0.00086
Nozzle #1	4.066769	4.072655	0.006	0.145			
Nozzle #1	5.072014	5.077893	0.006	0.116			
Nozzle #1	5.072814	5.080973	0.008	0.161			
Nozzle #1	6.065764	6.059252	-0.007	-0.107			
Nozzle #1	7.046718	7.045085	-0.002	-0.023			
Open	11.9725	11.99975	0.027	0.227		a:	0.0000E+00
Open	12.08531	11.99869	-0.087	-0.722		b:	1.0000E+00
Open	20.00167	20.00199	0.000	0.002		c:	0.0000E+00
Open	20.09555	20.00361	-0.092	-0.460			

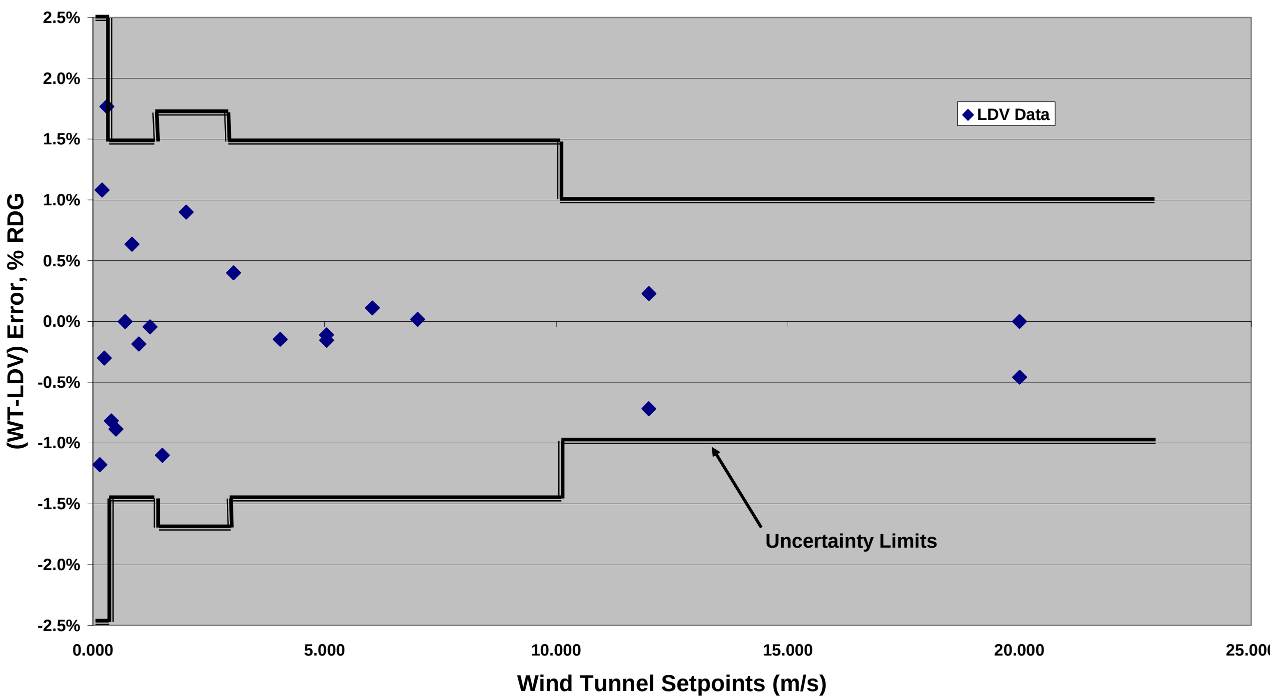
Comments:
Indicated velocities are standardized to indicated standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated polynomial fit coefficients. These coefficients are implemented in the wind tunnel software, no additional correction is required by the user.

ORNL Metrology Laboratory (ORNLML) certifies that the instrument listed was calibrated using standards whose accuracies are traceable to the National Institute of Standards and Technology (NIST) or have been derived from

Pitot Tube Calibration with AF07
September 19, 2003



AF07 LDV Calibration
September 19, 2003



The overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by the laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

OVERALL UNCERTAINTY OF BENCH TOP WIND TUNNEL

CALIBRATED RANGE	WTAP UNCERTAINTY	NOZZLE PLATE
0.15 to 0.3 m/s (30-60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60-250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250-600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600-1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000-9000 fpm)	1.0% of reading	Open

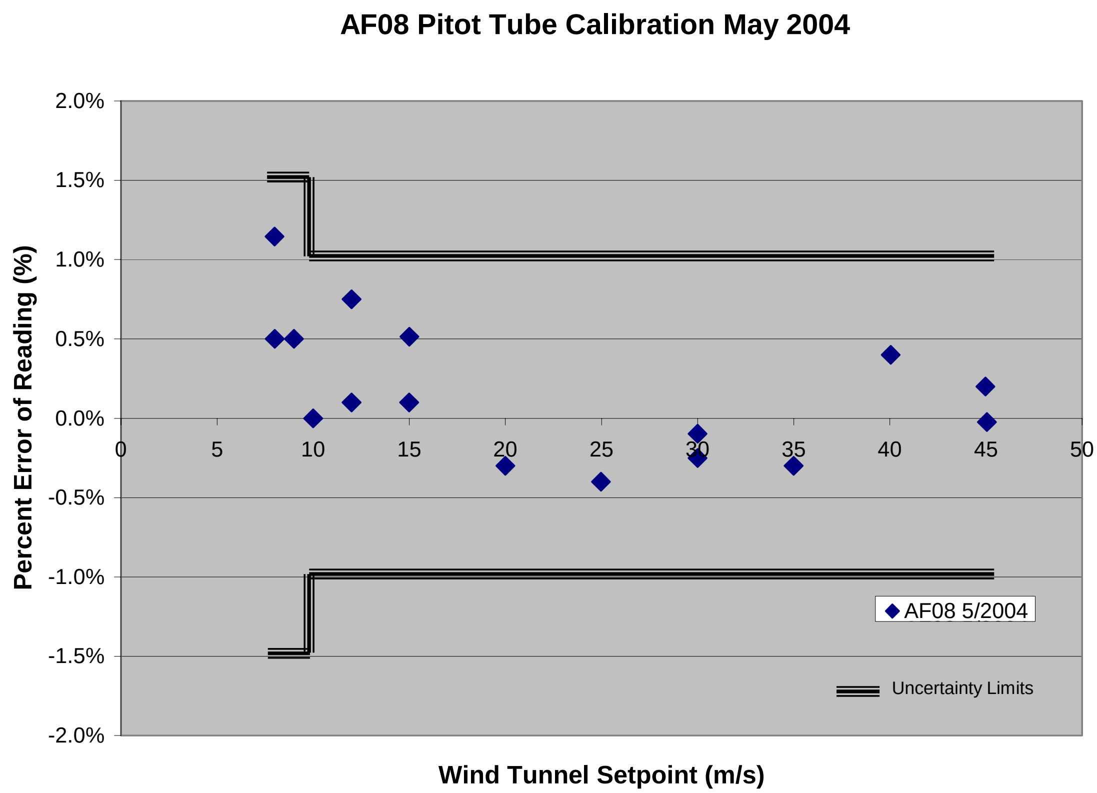
Report of Calibration - May 29-31, 2004

Instrument Identification: WTIP 2000, S/N AF08, TSI S/N 139
Instrument Serial: AF08
Descriptor: TSI Model 8390 Wind Tunnel
Span: 0.15 - 45 m/sec
Uncertainty: See attached chart

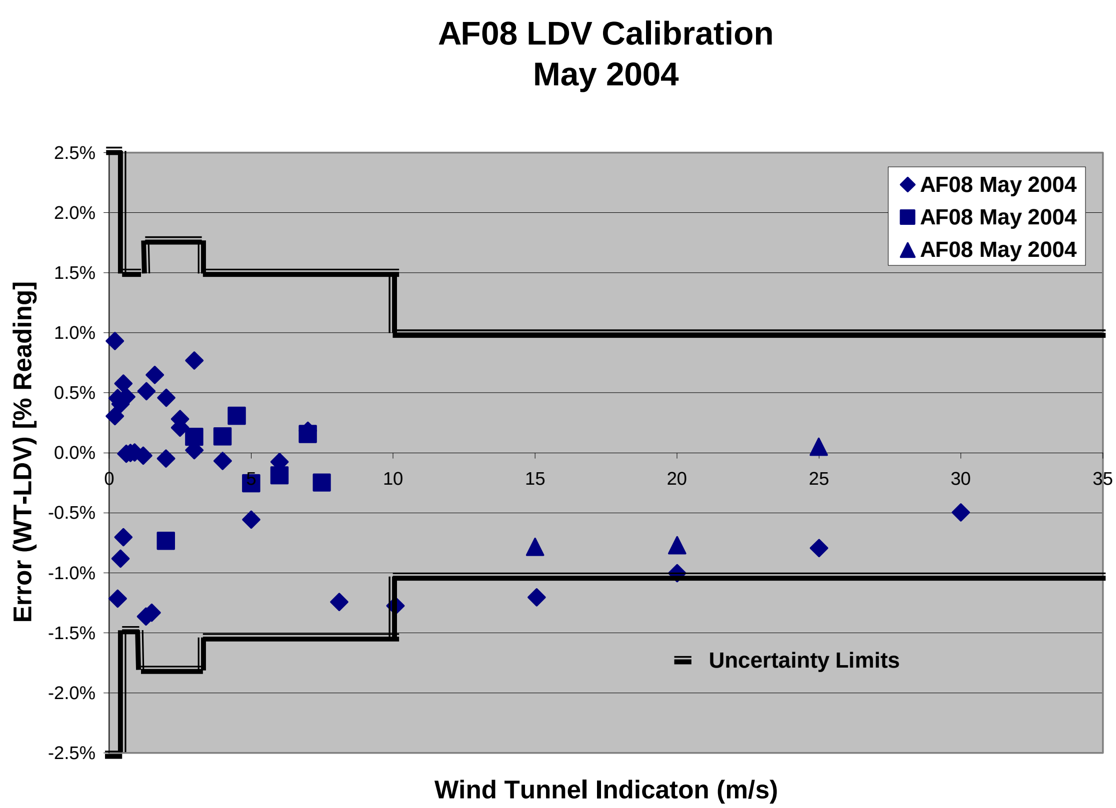
Calibration Conditions: 14.25 psia, 23 deg C, 45% RH
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	Standard Value (m/sec)	T.I. Indication (m/sec)	Error (TI-STD) (m/sec)	% Error (% Rdg)	Poly Fit	
Nozzle #2	0.200541	0.202406	0.002	0.922	a:	0.0042235
Nozzle #2	0.204308	0.20493	0.001	0.304	b:	0.99027
Nozzle #2	0.305516	0.301806	-0.004	-1.229	c:	0.005826
Nozzle #2	0.302043	0.303417	0.001	0.453		
Nozzle #2	0.404827	0.401261	-0.004	-0.889		
Nozzle #2	0.399668	0.401286	0.002	0.403		
Nozzle #2	0.504341	0.500798	-0.004	-0.707		
Nozzle #2	0.497978	0.500847	0.003	0.573		
Nozzle #2	0.597506	0.600293	0.003	0.464		
Nozzle #2	0.600635	0.600588	0.000	-0.008		
Nozzle #2	0.750276	0.750271	0.000	-0.001		
Nozzle #2	0.900247	0.900266	0.000	0.002		
Nozzle #2	1.20056	1.200275	0.000	-0.024		
Nozzle #1	1.335968	1.317741	-0.018	-1.383	a:	0.03716
Nozzle #1	1.326251	1.333059	0.007	0.511	b:	0.983066
Nozzle #1	1.535907	1.515448	-0.020	-1.350	c:	0.001635
Nozzle #1	1.61573	1.626197	0.010	0.644		
Nozzle #1	2.010703	2.009727	-0.001	-0.049		
Nozzle #1	2.011099	2.020305	0.009	0.456		
Nozzle #1	2.499741	2.504959	0.005	0.208		
Nozzle #1	2.498445	2.505493	0.007	0.281		
Nozzle #1	2.978305	3.001165	0.023	0.762		
Nozzle #1	3.000941	3.001549	0.001	0.020		
Nozzle #1	3.998387	3.995619	-0.003	-0.069		
Nozzle #1	5.021891	4.993908	-0.028	-0.560		
Nozzle #1	5.998827	5.994281	-0.005	-0.076		
Nozzle #1	6.984814	6.997559	0.013	0.182		
Open	8.202556	8.101909	-0.101	-1.242	a:	0.0000E+00
Open	10.21599	10.08733	-0.129	-1.275	b:	1.0000E+00
Open	15.23698	15.05562	-0.181	-1.205	c:	0.0000E+00
Open	20.20527	20.00443	-0.201	-1.004		
Open	25.19955	25.00106	-0.198	-0.794		
Open	30.146	29.99695	-0.149	-0.497		

Comments:
Indicated velocities are standardized to indicated standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated polynomial fit coefficients. These coefficients are implemented in the wind tunnel software, no additional correction is required by the user.



AF08 Pitot Tube Calibration May 2004
Percent Error of Reading (%)
2.0%
1.5%
1.0%
0.5%
0.0%
-0.5%
-1.0%
-1.5%
-2.0%
0
5
10
15
20
25
30
35
40
45
50
AF08 5/2004
Uncertainty Limits
Wind Tunnel Setpoint (m/s)



AF08 LDV Calibration
May 2004
Error (WT-LDV) [% Reading]
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
-0.5%
-1.0%
-1.5%
-2.0%
-2.5%
0
5
10
15
20
25
30
35
AF08 May 2004
AF08 May 2004
AF08 May 2004
Uncertainty Limits
Wind Tunnel Indicaton (m/s)

The overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by the laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

OVERALL UNCERTAINTY OF BENCH TOP WIND TUNNEL

CALIBRATED RANGE	WTAP UNCERTAINTY	NOZZLE PLATE
0.15 to 0.3 m/s (30-60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60-250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250-600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600-1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000-9000 fpm)	1.0% of reading	Open

OAK RIDGE NATIONAL LABORATORY
ENGINEERING SCIENCE AND TECHNOLOGY DIVISION

Report of Calibration - January 26, 2005

Instrument Identification: WTIP 2000, S/N AF09, TSI S/N 178

Instrument Serial: AF09

Descriptor: TSI Model 8390 Wind Tunnel

Span: 0.15 - 45 m/sec

Uncertainty: See attached chart

Calibration Conditions: 14.4 psia, 20.5 deg C, 13% RH

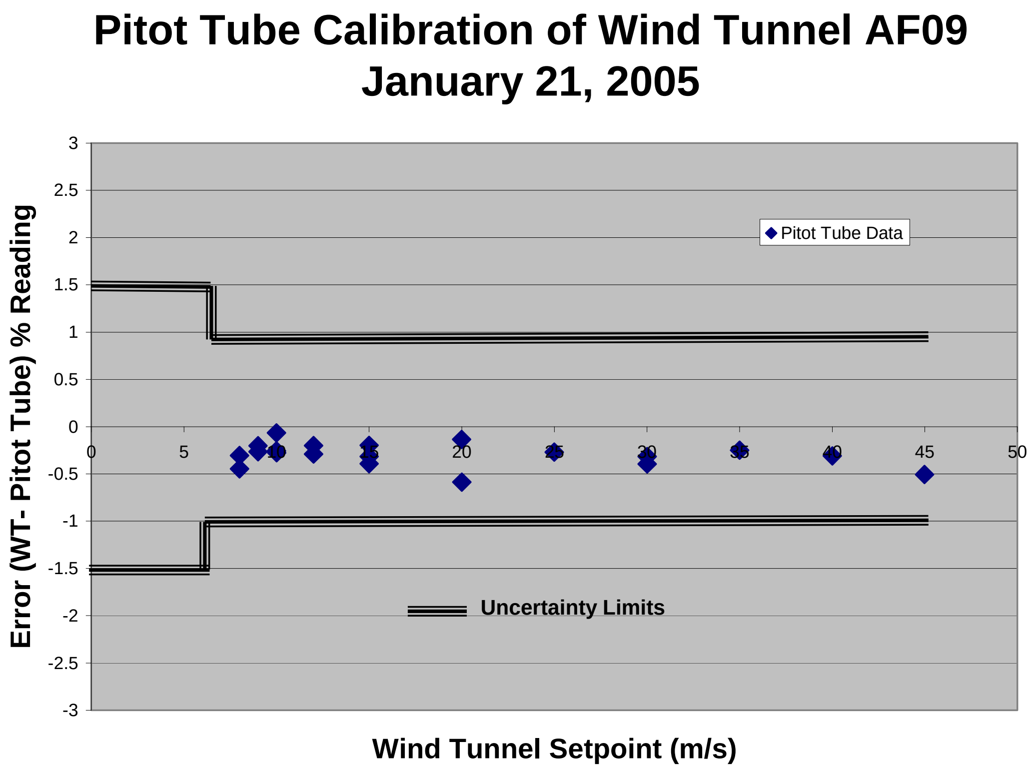
Standard Conditions: 14.7 psia, 21.11 deg C, 0% RH

Wind Tunn Config	Standard Value (m/sec)	T.I. Indication (m/sec)	Error (TI-STD) (m/sec)	% Error (% Rdg)	Poly Fit	
Nozzle #2	0.153578	0.153599	0.000	0.014	a:	0.005383
Nozzle #2	0.153845	0.153622	0.000	-0.145	b:	0.985827
Nozzle #2	0.178303	0.178372	0.000	0.039	c:	0.016243
Nozzle #2	0.178697	0.17839	0.000	-0.171		
Nozzle #2	0.203182	0.203212	0.000	0.015		
Nozzle #2	0.203249	0.203234	0.000	-0.007		
Nozzle #2	0.303599	0.302591	-0.001	-0.332		
Nozzle #2	0.45075	0.452268	0.002	0.337		
Nozzle #2	0.451598	0.452312	0.001	0.158		
Nozzle #2	0.602384	0.602748	0.000	0.061		
Nozzle #2	0.753639	0.753889	0.000	0.033		
Nozzle #2	0.95921	0.956576	-0.003	-0.275		
Nozzle #2	1.211075	1.211663	0.001	0.049		
Nozzle #2	1.2111	1.211731	0.001	0.052		
Nozzle #1	1.2698	1.273609	0.004	0.300	a:	0.075206
Nozzle #1	1.285507	1.273711	-0.012	-0.918	b:	0.943668
Nozzle #1	1.364009	1.360204	-0.004	-0.279	c:	0.006086
Nozzle #1	1.596939	1.600365	0.003	0.215		
Nozzle #1	1.597434	1.600711	0.003	0.205		
Nozzle #1	3.426322	3.452711	0.026	0.770		
Nozzle #1	3.449157	3.45274	0.004	0.104		
Nozzle #1	4.473589	4.445432	-0.028	-0.629		
Nozzle #1	5.958652	5.956386	-0.002	-0.038		
Nozzle #1	7.179039	7.184578	0.006	0.077		
Open	8.125	8	-0.125	-1.563	a:	0.0000E+00
Open	10.09	10	-0.090	-0.900	b:	1.0000E+00
Open	15.115	15	-0.115	-0.767	c:	0.0000E+00
Open	20.1	20	-0.115	-0.767		
Open	25.09	25	-0.100	-0.500		
Open	30.14	30	-0.090	-0.360		

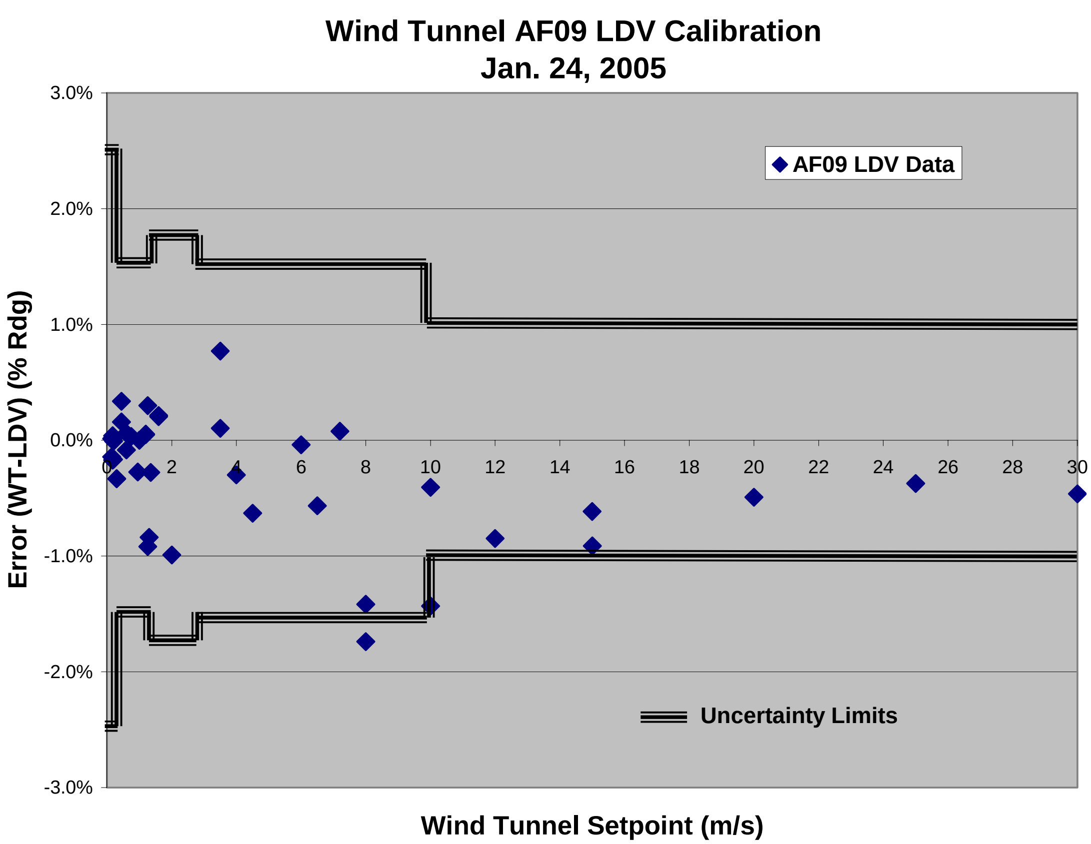
Comments:

Indicated velocities are standardized to indicated standard conditions.
T.I. Indication' presents wind tunnel indication after correcting with indicated polynomial fit coefficients. These coefficients are implemented in the wind tunnel software, no additional correction is required by the user.

ORNL Metrology Laboratory certifies that the instrument listed was calibrated using standards whose accuracies are traceable to the NIST



Pitot Tube Calibration of Wind Tunnel AF09
January 21, 2005
Pitot Tube Data
Uncertainty Limits
Error (WT- Pitot Tube) % Reading
Wind Tunnel Setpoint (m/s)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
5
10
15
20
25
30
35
40
45
50



Wind Tunnel AF09 LDV Calibration
Jan. 24, 2005
AF09 LDV Data
Uncertainty Limits
Error (WT-LDV) (% Rdg)
Wind Tunnel Setpoint (m/s)
3.0%
2.0%
1.0%
0.0%
-1.0%
-2.0%
-3.0%
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

The overall uncertainty is the combined uncertainties contributed by the static uncertainties of the instrumentation package, turbulence within the wind tunnel (as determined by the laser Doppler measurements throughout the velocity range), standard velocity measurement contributions (pitot and LDV systems), and curve-fit bias errors in correcting the wind tunnel velocity. Over the full range of use of the wind tunnel, the overall uncertainty was calculated to be as follows:

OVERALL UNCERTAINTY OF BENCH TOP WIND TUNNEL

CALIBRATED RANGE	WTAP UNCERTAINTY	NOZZLE PLATE
0.15 to 0.3 m/s (30-60 fpm)	2.5% of reading	#2
0.3 to 1.25 m/s (60-250 fpm)	1.5% of reading	#2
1.25 to 3 m/s (250-600 fpm)	1.75% of reading	#1
3 to 7.5 m/s (600-1500 fpm)	1.5% of reading	#1
7.5 to 10 m/s (1500-2000 fpm)	1.5% of reading	Open
10 to 45 m/s (2000-9000 fpm)	1.0% of reading	Open

9.0 References

[1]Hardy, J. E., et. al. (2002) "Automation and Characterization of US Air Force Bench Top Wind Tunnels," 48th International Instrumentation Symposium, San Diego, C

[2]Taylor, B. N. and C. E. Kuyatt., "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results", NIST Technical Note 1297, Washington, D. C., 1993.

[3] McKnight, T. E. et al., "Wind Tunnel Automation Package P/N 8390AF User's Manual," Oak Ridge National Laboratory, September 2001.

[4] Mease, N. E. et al., "Airspeed Calibrations at the National Institute of Standards and Technology," Proceedings of the 1992 Measurement Science Conference, Ahaheim, CA. 1992.

[5] Report of Calibration of Air Speed Instrumentation, Pitot-Static Tube Serial Number P65041, NIST Gaithersburg, MD September 15, 2000.

[6] Bean, V. E. and J. M. Hall., "New Primary Standards for Air Speed Measurement at NIST," Proceedings of NCSL Workshop and Symposium, Session 4E, 1999.